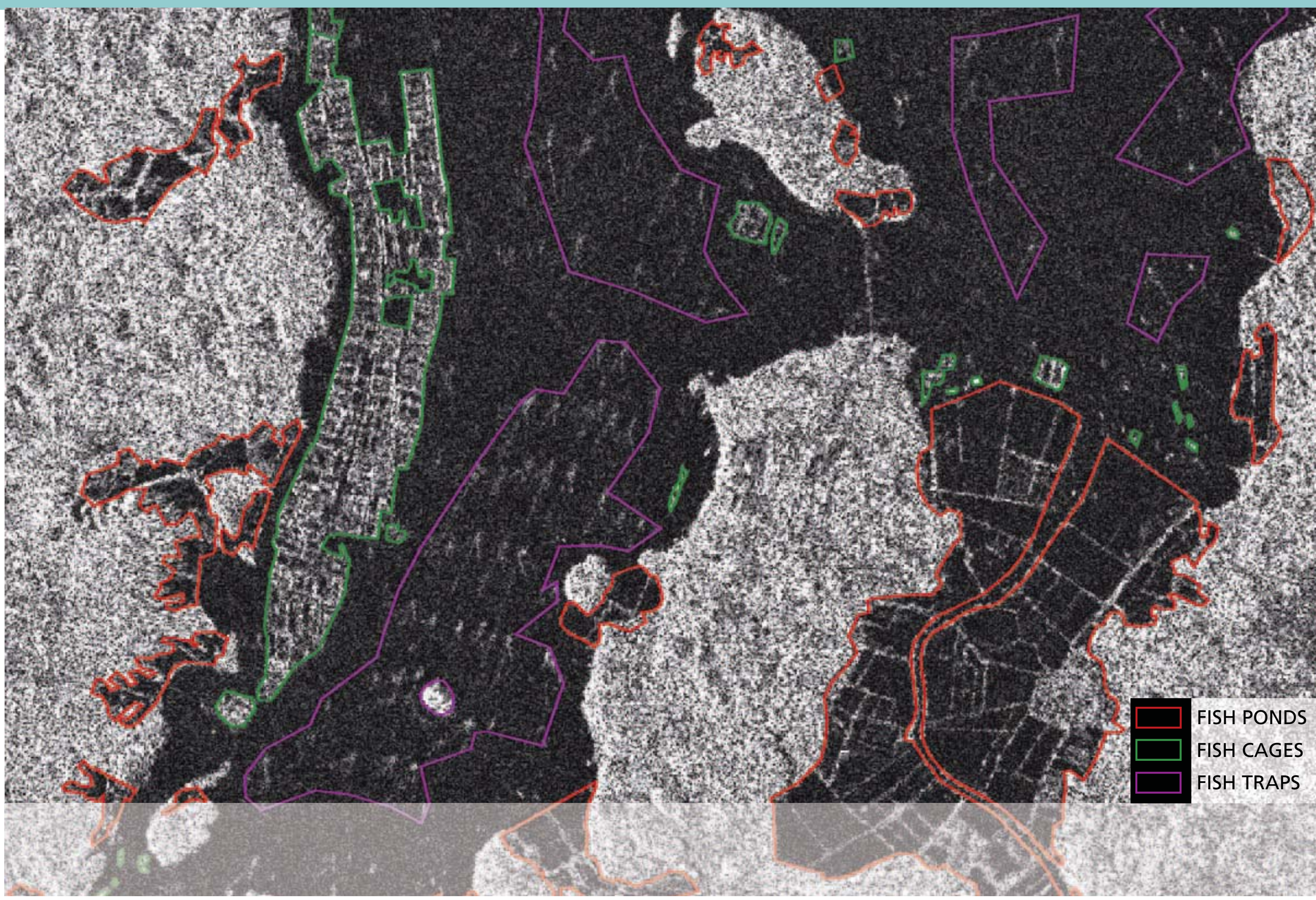
ISSN 0429-9345

FAO
FISHERIES
TECHNICAL
PAPER

459

Mapping coastal aquaculture and fisheries structures by satellite imaging radar

Case study of the Lingayen Gulf, the Philippines



459 Mapping coastal aquaculture and fisheries structures by satellite imaging radar FAO

Cover image:
Fish cages, fish traps and fish ponds in the Lingayen Gulf area, northern Luzon, the Philippines. RADARSAT 1 SAR fine resolution image (acquired 4 February 2001).

Copies of FAO publications can be requested from:

SALES AND MARKETING GROUP
Information Division
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla
00100 Rome, Italy

E-mail: publications-sales@fao.org
Fax: (+39) 06 57053360
Web site: http://www.fao.org

Mapping coastal aquaculture and fisheries structures by satellite imaging radar

Case study of the Lingayen Gulf, the Philippines

FAO FISHERIES TECHNICAL PAPER
459

by
Carlo Travaglia
Environment and Natural Resources Service
FAO Sustainable Development Department
Rome, Italy

Giuliana Profeti
SAR Image Processing
Florence, Italy

José Aguilar-Manjarrez
Inland Water Resources and Aquaculture Service
FAO Fisheries Department
Rome, Italy

and
Nelson A. Lopez
Bureau of Fisheries and Aquatic Resources
Manila, the Philippines

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2004

ISBN 92-5-105114-3

FOREWORD

Cooperation between the FAO Remote Sensing Center (now Environment and Natural Resources Service (SDRN)) and the Inland Water Resources and Aquaculture Service (FIRI) began in 1983 with the joint planning of the international training course "Remote Sensing Applications to Inland Fisheries and Aquaculture", held at FAO headquarters in September 1984. Its aim was to raise awareness among fishery technical and management officers of the very positive remote sensing and GIS applications which were relevant to their work. In this framework and with the same objectives in the subsequent years training courses, pilot studies and operational projects have been jointly conducted worldwide.

A result of this longstanding cooperation has been the development and field testing, under operational conditions, of new remote sensing methodologies for specific fisheries requirements, such as aquaculture site selection, wetlands monitoring, shrimp farms inventory and monitoring and others. These methodologies have been widely disseminated to potential users in both the fields of fisheries and remote sensing through FAO publications.

The paper we present here aims to introduce a cost-effective new methodology for accurate inventory and monitoring of coastal aquaculture and fisheries structures.

Jiansan Jia
Chief, Inland Water Resources and
Aquaculture Service (FIRI)

Jeff Tschirley
Chief, Environment and Natural Resources
Service (SDRN)

Distribution:

FAO Members and Associate Members
FAO Fisheries Department
FAO Fisheries Officers in FAO Regional and Subregional Offices
FI Marine Fisheries and Aquaculture Mailing Lists

ACKNOWLEDGEMENTS

The authors are greatly indebted to all who assisted in the implementation and completion of this study by providing information, advice and facilities.

The administrative support of the Bureau of Fisheries and Aquatic Resources (BFAR), the Philippines, Director Malcolm I. Sarmiento, Jr. and of the other Bureau's officers at the regional and provincial level is hereby acknowledged. Likewise the field assistance of Leodegario Abarra, Nestor Botacion, Catherine Rabadon, Mea Baldonado, Lina Bravo, Felita Ugaban, Roberto De Vera, Jr. and Wilfredo Basa is gratefully appreciated, as well as the participation in the field team of the BFAR-IFAD Technical Staff; James Villanueva, Rodolfo Tigue, Roy Garcia and Edgardo Amurao.

The provision by the European Space Agency (ESA) of satellite radar data at nominal cost, acquired according to the authors specifications, greatly facilitated the work and has been sincerely appreciated.

The authors are greatly indebted to Roberto Carlà of the Institute of Applied Physics of the Italian National Research Council; Pierre-Philippe Mathieu, Earth Observation Science and Applications, European Space Agency; James McDaid Kapetsky, Senior Fishery Resources Officer (FAO-FIRI retired) and Uwe Barg, Fishery Resources Officer (FAO-FIRI) for their critical review of the manuscript.

Claudia Riva assisted in preparing data for the field verification work and in the literature review. Desktop publishing work was by Nadia Pellicciotta.

Travaglia, C.; Profeti, G.;
Aguilar-Manjarrez, J.; Lopez, N.A.
Mapping coastal aquaculture and fisheries structures by satellite imaging radar.
Case study of the Lingayen Gulf,
the Philippines.
FAO Fisheries Technical Paper. No. 459. Rome, FAO. 2004. 45p.

ABSTRACT

Inventory and monitoring of coastal aquaculture and fisheries structures provide important baseline data for decision-making in planning and development, including regulatory laws, environmental protection and revenue collection. Mapping these structures can be performed with good accuracy and at regular intervals by satellite remote sensing, which allows observation of vast areas, often of difficult accessibility, at a fraction of the cost of traditional surveys.

Satellite imaging radar (SAR) data are unique for this task not only for their inherent all-weather capabilities, very important as aquaculture activities mainly occur in tropical and subtropical areas, but essentially because the backscatter from the structure components allows for their identification and separation from other features.

The area selected and object of the study has been Lingayen Gulf, sited in Northwestern Luzon Island, the Philippines, where all these structures of interest occur.

Field verification of the methodology resulted in the following accuracy: fishponds 95 percent, fish pens 100 percent. Mapping accuracy for fish cages was estimated at 90 percent and for fish traps at 70 percent.

The study is based on interpretation of SAR satellite data and a detailed image analysis procedure is described. The report aims at the necessary technology transfer for an operational use of the approach indicated in other similar environments.

Keywords: Aquaculture; Fisheries structures; Geographic Information Systems; Lingayen Gulf; Philippines; Remote Sensing; SAR; Satellite imaging radar.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 BACKGROUND: THE SRI LANKA EXPERIENCE ON MAPPING INLAND AQUACULTURAL FARMS

In 1999, in the framework of the assistance provided to the FAO project TCP/SRL/6712 "Revitalization and Acceleration of Aquaculture Development" in its inventory and monitoring of shrimp farms in northwestern Sri Lanka, the FAO Services "Environment and Natural Resources" (SDRN) and "Inland Water Resources and Aquaculture" (FIRI) jointly conducted a pilot study with a view to develop and field test adequate methodologies for future use in similar environments elsewhere.

Inventory and monitoring of shrimp farms are essential tools for decision-making on aquaculture development, including regulatory laws, environmental protection and revenue collection. The Sri Lanka Government required up to date information on the spatial distribution of shrimp farms in order to enforce development regulations and to ensure a productive environment for shrimp farming with the least impact on the other uses of land and water resources. The FAO project TCP/SRL/6712 provided an unique opportunity to test under operative conditions an innovative methodology for inventory and monitoring of shrimp farms and the support of a field team for the ground verification of the results and, thus, of the methodology's accuracy.

It was immediately evident to the authors that satellite imaging radar was the only tool available for achieving good results. Synthetic Aperture Radar (SAR)[1] data are unique for mapping shrimp farms, not only for their inherent all-weather capabilities, very important as shrimp farms occur in tropical and subtropical areas, but mainly because the backscatter from the dykes surrounding the ponds allows for recognition and separation of shrimp ponds from all other water covered surfaces. This is not possible with satellite data such as Landsat or SPOT, operating in the visible and near/mid infrared portion of the electromagnetic spectrum, because of the frequent clouds coverage and of the difficulty of discriminating the artisanal shrimp farms, with their small area and irregular shape, from other water covered surfaces, such as flooded rice paddies and flooded areas.

ERS SAR satellite data, acquired over the area in 1996, 1998 and 1999, were processed for shrimp farms inventory and the resulting information was compared to substantiate changes and trends in the development of shrimp farms.

Apart from the advantages reported previously (all-weather capabilities and easy discrimination of shrimp farms from all other water covered surfaces), employing SAR data for shrimp farms inventory and monitoring provides two more benefits.

The first is timeliness, as satellite data are acquired regularly and this allows for the extraction of up-to-date information. Results of the pilot study indicate that shrimp farming is growing at a very rapid rate in northwestern Sri Lanka and that the surface is much more extensive than reported in official data. The second, an important advantage over traditional surveys, is that the resulting digital radar maps can be incorporated into an existing Geographic Information System (GIS). Once incorporated into the GIS, the shrimp pond locations can be evaluated in terms of a number of characteristics of site suitability and also with regard to prior uses of the land. In this way the development of shrimp farming can be better planned and regulated in a more rational way than is possible without such information. In this regard, it is important to note that such information is of use not only to government, but valuable also to associations of commercial shrimp farmers whose underlying

[1] See Glossary in section 5 for a complete definition of SAR.

purpose is to maintain a dependable supply of good quality products at competitive prices.

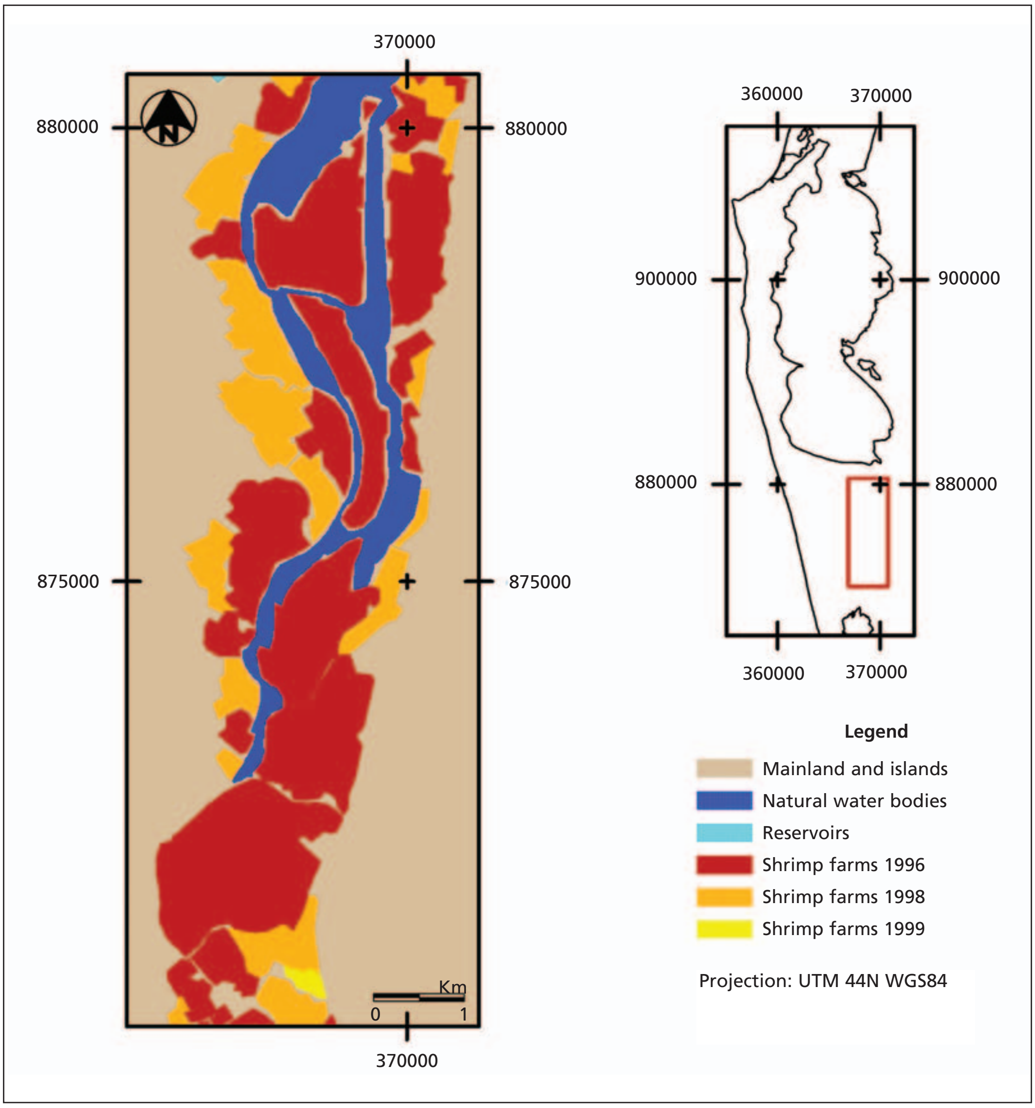
The need for shrimp farm mapping is both qualitative and quantitative. In this regard, the results of the pilot study show that the location of commercial shrimp farms can be accurately obtained, and their collective size estimated with satisfactory results. It is sometimes difficult to estimate the area coverage of individual, small sized shrimp farms, but it is generally possible to estimate with good approximation the area coverage of a cluster of shrimp farms.

The results of the study are reported in Table 1 which indicates the rapid expansion of the shrimp farm industry in northwestern Sri Lanka, which has increased its area coverage by 44.1 percent in less than three years. Figure 1 shows the expansion of shrimp farms in the Dutch Canal test site.

TABLE 1
Total surface covered by shrimp farms, Sri Lanka study (Travaglia, Kapetsky and Profeti, 1999)

Date of image acquisition	Area *(km^2)*	Increase *(%)*
18 April 1996	61.3978	-
16 October 1998	86.5289	40.9
5 March 1999	88.4605	2.2
Difference 1999–1996	**27.0627**	**44.1**

FIGURE 1
Shrimp farms in the Dutch Canal test site, Sri Lanka (Travaglia, Kapetsky and Profeti, 1999)



Ground verification indicated an accuracy of 86 percent. Subsequent calibration of the interpretation keys resulting from the ground truthing increased the accuracy of the approach, thus the final methodology is more than 90 percent accurate.

To disseminate this new approach to potential users, a technical report was prepared by Travaglia, Kapetsky and Profeti (1999), and is available on the Web at http://www.fao.org/sd/EIdirect/EIre0077.htm.

1.2 OBJECTIVE OF THE PRESENT STUDY

The pilot study in Sri Lanka demonstrated the usefulness of Synthetic Aperture Radar (SAR) satellite data for inventory and monitoring of shrimp farms, and in general, of fishponds with high accuracy. The satellite remote sensing approach was found to be economically viable, as the value of shrimps more than justifies an accurate inventory and monitoring of the development of the farms.

Although hardware (PC-based digital imagery analysis systems) and software (ERDAS, ENVI, ArcView or equivalent) are now usually available in remote sensing agencies and laboratories, the methodology requires a good background in imaging radar theory and a considerable practice in handling and processing SAR data. However, as indicated, only satellite imaging radar (SAR) allows for the accurate mapping of fishponds.

Having developed and field tested a methodology for inventory and monitoring of inland fisheries structures (Travaglia, Kapetsky and Profeti, 1999), which could be applied in similar environments worldwide, the authors decided to expand the study to cover other structures, such as fishpens, fish cages and fish traps.

Therefore, the objective of the present study is to develop and field test a methodology, based on satellite imaging radar (SAR) to inventory and monitor coastal aquaculture and fisheries structures, including accuracy evaluation. It is aimed at the general fisheries and aquaculture public, governmental administrators and planners and remote sensing and GIS specialists.

The selection of a test area in which to conduct the study was the first problem to be solved: the area needed to include all of the structures of interest; furthermore assistance from a local team was necessary for baseline information and field checking of the results. The Lingayen Gulf, in northern Philippines, where all structures under study are present was thus selected as test area and the assistance to this exercise by the Bureau of Fisheries and Aquatic Resources of the Philippines was secured.

1.3 DESCRIPTION OF THE TEST AREA

Lingayen Gulf is located in the northwestern coast of Luzon Island, the Philippines at coordinates between 16° and 17° North latitude and 119° and 121° East longitude. The test area is a little smaller, being the area covered by the satellite data used in the study (Table 2 and Figure 2).

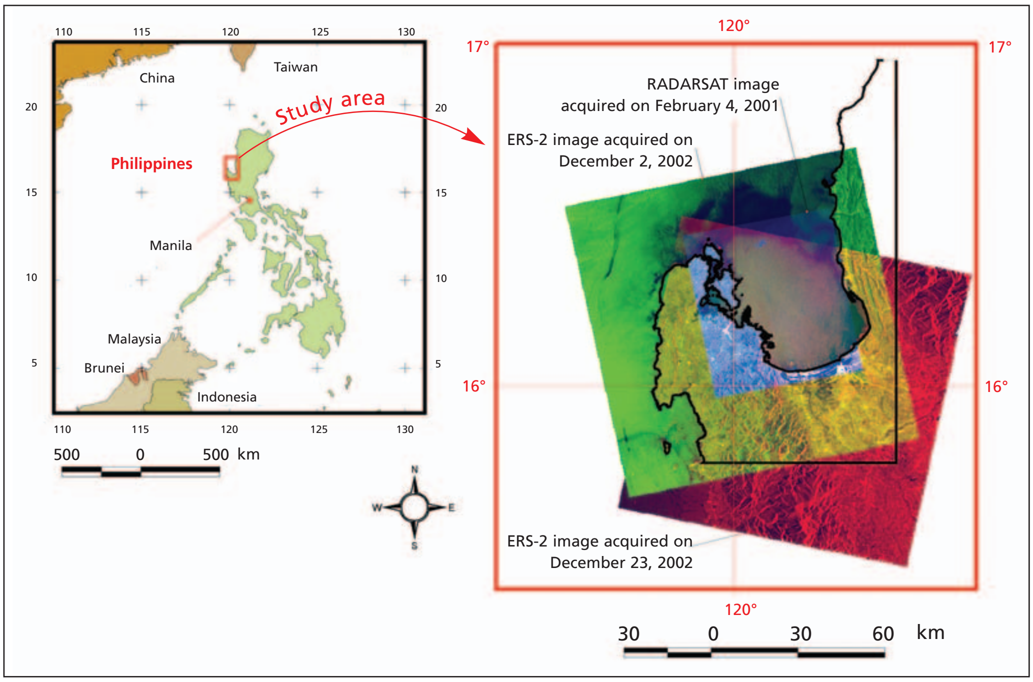
The gulf is bounded on the east by the steep slopes of the Central Cordillera, in the south by the northern portion of the Luzon Central Plain and on the west by low hills, the northernmost features of the Zambales Mountains, continuing into the sea with the several islands. The gulf is a semi-circular embayment enclosing an area of approximately 2 100 km^2 with 160 km of coastline from Cape Bolinao to Poro Point.

The northern portion of Luzon Central Plain is a vast alluvial lowland drained by several rivers, of which the Agno River, with its large catchment of more than 5 000 km^2, is the most important. The area experiences severe floods during wet season mainly due to overflow by the Agno River, with extensive damage to fisheries and agricultural crops.

TABLE 2
Coordinates of the study area

Geographic, Ellipsoid Clarke 1866, datum Luzon	Upper left corner *(decimal degrees)*	Lower right corner *(decimal degrees)*
Latitude	17.00	15.75
Longitude	119.75	120.50

FIGURE 2
The study area and the zones covered by the satellite data



Five major rivers drain into the gulf: Bauang and Aringay, flowing from the Central Cordillera; and Patalang-Bued, Dagupan and Agno flowing northward from the Central Plain but originating in the Central Cordillera. These rivers affect the physico-chemical characteristics of the gulf. Sediment loads of Agno and Patalan-Bued Rivers include sediment and contributions from the mines located in Benguet on the upstream segment of the rivers.

Lingayen Gulf is a major area for capture fisheries, aquaculture and coastal tourism. From 1980 to 1984, an average annual catch of 2 000 tonnes was landed by commercial trawlers, and a yearly mean of 6 000 tonnes by small-scale fishermen. The gulf ranked second highest nationwide in brackishwater pond yield, with a fish production of over 1 tonne/ha in 1984 and 1985. Most recently the gulf supplies almost one-third of the farmed milkfish (*Chanos chanos*, Forsskål, 1775) to Metro Manila. Fish production increased since the early 1990s when sea cage farming in pen and cages were allowed by the coastal municipalities. Approximately fifty tourist-oriented establishments are located along the 160 km coastline of the gulf, or about one lodging place for every 3 km stretch of shore (BFAR, 2001).

But like most of the country's coastal waters, the gulf is beset by complex problems which make multisectoral planning necessary. Capture fisheries exert very intense pressure on the gulf's fish resources. With over 12 000 fishermen and 7 000 boats in the 18 coastal municipalities and cities surrounding the gulf, catch per unit effort (CPUE) has reached a suboptimal level of less than 1 kg/fisherman/day. As a result, small-scale fishing has become the most marginal occupation in Lingayen Gulf. The use of explosives and chemicals to augment the catch has contributed to rapid habitat degradation and diminution of fish stocks. Pollution of the gulf with silt, domestic and industrial waste, including mine tailings, has caused deterioration of the environment and dwindling productivity, particularly in the aquaculture industry (BFAR, 2001).

Aquaculture in the Lingayen Gulf started as early as 1920s by converting privately owned mangrove areas, nipa and rice land into brackishwater fishponds. In 1986 there were a recorded 16 000 hectares fishponds occurring in La Union and Pangasinan, the two coastal provinces of the gulf.

The aquaculture industry in Lingayen Gulf historically established as early as 1920s expanded into mariculture with the introduction of seafarming technologies in seaweeds and bivalve culture. It then proliferated in the early 1990s when the Fisheries Code of the Philippines (Republic Act 8550) devolved the management power of the municipal waters to the local government units (under the city and municipal administration). By virtue of local fisheries ordinances, individual municipalities and cities within the gulf allotted areas for mariculture (in pens and cages) and fish traps (fish corrals) in designated zones. However, poor planning and lack of effective monitoring, have caused depletions of corals, recurrent fish kills and eutrophication of the gulf water. Brackishwater fishponds are affected by pollution brought about by sludge and sediments formation from the substrates of fish pens, fish traps and fish cages which are flushed by the current along the riverine system of the gulf. On the other hand, fish cages, fish pens and fish traps operators along the bay and estuarine areas of the gulf, blame the brackishwater fish pond effluents to have caused the mass mortalities of farmed and wild fishes in the coves of the gulf.

To date however, there are no available baseline statistical data as to what amount of the total brackishwater areas are still engaged in the traditional fishpond farming and how many cages or pens are operational in each particular city or municipalities. Production data from aquaculture in the province, although being monitored by the provincial offices of the Bureau of Agricultural Statistics are still inaccurate and require updating.

There has been no previous study or inventory records of existing operational fish pens and marine seacages, except the registered records of present operators in the Gulf by the Local Government Units (LGUs) indicating an increasing numbers of fish pens and fish cages which are concentrated mostly along the province of Pangasinan compared to previous years (BFAR, 2001).

During the course of the field survey for the present study, out of the fishpond areas verified, roughly 80 percent were non operational during the time of survey and were either found to be idled due to losses by floods, water management problems due to siltation and pollutions resulting in fish kills due to oxygen depletion, or were just waiting for the best farming season (average: 1–2 crops per year). Some farms, particularly those close to urban areas are presently converted into commercial lots, as in the case of Barangay Salapingao where previous fishpond areas are now reclaimed as residential areas. The presence of numerous and continuously increasing number of cages, pens and fish traps within the gulf areas indicates that seacage farming and artisanal fishing are now the preferred fisheries industry in the entire locality. Actually, a fish pen or a fish cage costs about one-tenth of a fishpond and may produce three times more.

1.4 DESCRIPTION OF THE STRUCTURES: FISH PENS, CAGES AND TRAPS

Fish pens

Fish pens are fenced, netted structures fixed to the bottom substrate and allowing free water exchange. In the intertidal zone, they may be solid-walled. The bottom of the structure, however, is always formed by the natural bottom of the water body where it is built; usually coastal e.g. in bays, fjords, lagoons, but also inland e.g. in lakes, reservoirs. A pen generally encloses a relatively large volume of water (Beveridge, 1987; Muir, 1995; Shehadeh, 2002).

Fish pens in the Lingayen Gulf are made up of nets on all sides and utilize the sea bed as the bottom enclosure or often are provided with extended bottom nettings (Figure 3). A pen is usually supported by fixed rigid frameworks of coconut posts or bamboo poles and wooden frames, making it a stationary farming structure. The bulk

FIGURE 3
Fish pens in Lingayen Gulf (Photo: BFAR/N.A.Lopez, 2003)

of mariculture activities using fish pens is concentrated in the coastal and inland waters of Bolinao, Dagupan and Binmaley in Pangasinan and Aringay in La Union. The number of fishpens in these municipalities in 1996 amounted to 685 units spread across an area of 41.1 hectares. The surface enclosed by fish pens varies from one-fourth of a hectare to 2 hectares or more (BFAR, 2001).

The most common species for culture is milkfish (*Chanos chanos*). At present, fishpen operators need to extend their culture period from 5 to 6 months in order to produce milkfish of marketable size (=500 g/piece). In previous years, three months were sufficient to produce marketable sized fish. Harvest frequency has been reduced from 4 to 3 or 2 cycles per year. The major reason is the deteriorating water quality from pollution caused by low water exchange resulting from high stocking densities, excessive feeding and the unregulated establishments of these structures in most of the coastal municipalities.

It has been also noted most recently that the excessive use of commercial formulated feeds for milkfish in fish pens has drastically contributed to the formation of massive sludge deposits on the substrate that decompose to a deadly form of hydrosulfates contributing to the mass mortalities of fish stocks during tidal overturns and inclement weather conditions. As the pens are stationary and fixed in shallow areas, unlike cages which are positioned in deeper portions and can be moved, most fish kills do occur in fish pen belt areas rather than in fish cages. Both farming structures, however, are stocked with high densities of fish and require daily intensive feeding which also pollutes the water environment.

Fish cages

Fish cages are rearing facilities closed at the bottom as well as on the sides by wooden, mesh or net screens. This allows natural water exchange through the lateral sides and in most cases below the cage (Beveridge, 1987).

Fish cages in Lingayen Gulf have evolved from the old traditional fixed cage consisting of a net bag supported by bamboo posts driven into the bottom of a lake or river for fish fattening or grow-out purposes to floating net cages using suspended bottom net enclosures supported with bamboo poles, wooden planks, floats and fixed anchors. With the innovation of milkfish broodstock cages, steel pipes supported with styrofoam floats and concrete anchors were later designed for longer use. Most recently, imported and locally modified Norwegian cages are employed for the mass culture of milkfish in the gulf (Figure 4). Shapes and sizes of individual cages vary from quadrangular (10 x 10 x 8 m) partitioned into a cluster of compartments, or cylindrical (10–20 m x 10 m).

FIGURE 4
Fish cages in Lingayen Gulf (Photo: BFAR/N.A.Lopez, 2003)

In 1995, when mangrove conversion into fishponds was prohibited, most fish farmers engaged themselves into mariculture of milkfish (which were traditionally cultured in fishponds) utilizing fish cages and fish pens in rivers (estuarine areas) and open sea (within the gulf area) since they have no other alternatives to expand their milkfish farming activities. Most recently, some farmers diversified their mariculture practices not only in milkfish grow-out, but also in fattening and intensive farming of groupers and other high valued commercial species in pens and cages.

As with fish pens, the main farming areas for fish cages are found in Bolinao, Anda, Sual, and Dagupan in Pangasinan and Aringay and Sto. Tomas in La Union constituting 114 units covering an approximate area of 8 hectares at the end of 1996. In 2001 however, a recorded 1 170 units were operating in Bolinao and 1 139 units were reported in Dagupan. The continued proliferation of the fish cages in the gulf has been a long standing issue with severe consequences in ecological and socio-economic imbalance. Most common social and environmental impacts are the displacement of artisanal fishers, restriction of navigational routes and deterioration of water quality (BFAR, 2001).

Fish traps

A fish trap is a device designed to encourage fish to enter a confined space and to prevent fish from leaving once they have entered. A fish trap may be of many sizes and configurations but usually it has an entrance, some form of non-return structure and a capture chamber. May be made of local materials or commercially bought wire mesh or netting. A fish trap may be set unbaited or baited depending on the target species (Welcomme, 2001).

Traditional fish traps in the Lingayen Gulf are bamboo stake traps or fish corrals consisting of three parts: leaders, playground and cod-end (Figure 5). Leaders, whose purpose is to guide the fish into the trap, are made of bamboo stakes, netting or branches. Their length varies from 10 to 300 metres, depending on the size of trap. The playground is either a labyrinth, C-shaped or triangular enclosure constructed of bamboo, or wooden stakes driven into the sea-bed, with or without wire netting which has hexagonal meshes. Some larger traps have two playgrounds. The exit from the playground area guides the fish into the cod-end, from where they are scooped. The cod-end is semi-circular, circular or rectangular, with a bamboo or wooden stake frame and covered by polyethylene net and/or wire netting.

The fish corral fisheries ranks fourth after gill nettings, baby trawls and hook and line capture fisheries in Lingayen Gulf with about 7 percent of the total municipal fishers engaged in this type of fishing. This fishery is practiced only along the intertidal zones with vast seagrass beds. The most common target species of fish corrals are the rabbit fishes (*Siganus* spp.) at sizes ranging from 6.8 to 19.4 cm with a modal length of 11.2 cm, this size range is considered too small as this species can potentially reach lengths of 40 cm. Other commercial species which are caught in fish traps and fish corrals are varieties of *Leiognathus, Penaeus* spp., *Scatophagus, Carangoides, Mugil, Rastrilleger* and crustaceans.

FIGURE 5
Fish traps in Lingayen Gulf (Photo: BFAR/N.A.Lopez, 2003)

As of 2001, more than 1 578 units of fish corrals were censused in the general area but numerous fish traps abounds the river inlets and shallow portions of the Gulf such as the fixed or passive types of fishing gears like the fyke nets, fish pots and lever nets at densities which often crowd the passage ways and corridors. These passive types of fishing gears compete with the active types of fisheries for the same fishing grounds. For example, the areas for fish corrals, lever nets and fish traps which are fixed, are the same areas where gill net and hook and line fisheries are also being operated (BFAR, 2001).

2. Methodology

2.1 DATA AND SOFTWARE USED

The study area is completely covered by two ERS-2 SAR images acquired on 2 December and 23 December 2002 respectively (Figure 2 and Table 3). The spatial resolution of ERS-2 SAR images is of 12.5 x 12.5 m. The two images were provided by the European Space Agency (ESA), in the context of their scientific research programme, in the Ellipsoid Geocoded Format (GEC). These images are system and ground range corrected, and were georeferenced and rectified into the Universal Transverse Mercator Projection (ellipsoid WGS84, zone 51 N). They have not been corrected for terrain distortion, as this was not necessary, the aquaculture and fisheries structures occuring in flat areas.

The two images were specifically acquired by ESA for this study, by selecting two acquisitions made during descending and ascending orbits with the least possible time interval in-between.

Orbit direction during the acquisition is extremely relevant because in descending orbits the scanning direction of the sensor is approximately opposite to that in ascending orbits. This in turn influences the characteristics of the SAR images, in which features are enhanced in a complementary way, as described in section 2.3.

TABLE 3
Characteristics of the satellite data used

Image type, pixel size	Orbit, frame	Heading, path *(degrees from North)*	Acquisition date *(year/month/day)*	Corner coordinates		
					N	E
ERS-2 SAR GEC[1] 12.5 x 12.5 m	39830, 315	347.348 ascending	2002/12/02	UL	16.54	119.48
				UR	16.73	120.39
				LR	15.82	120.58
				LL	15.64	119.68
	40123, 3285	192.640 descending	2002/12/23	UL	16.52	119.84
				UR	16.33	120.74
				LR	15.42	120.54
				LL	15.61	119.64
RADARSAT-1 SAR SGF[2] 6.25 x 6.25 m	27423, path image[3]	347.318 ascending	2001/02/04	UL	16.45	119.84
				UR	16.54	120.30
				LR	16.04	120.40
				LL	15.95	119.94

[1] Ellipsoid Geocoded Image. [2] SAR Georeferenced Fine resolution. [3] Floating along-track between two frames.
UL= Upper Left, UR=Upper Right, LR= Lower Right, LL=Lower Left.

A RADARSAT-1 SAR image acquired on 4 February 2001 in the Georeferenced Fine Resolution (SGF) format was purchased from RADARSAT International. Its ground resolution is of 6.25 x 6.25 m. This image is also ground range and system corrected, and has been georeferenced and rectified into the geographic system, ellipsoid WGS72. It does not cover the entire study area, but includes the zones where the majority of the aquaculture and fisheries structures are located (Figure 2 and Table 3).

In the study of coastal features and of some aquaculture and fisheries structures, the tide stage at the time of acquisition of the radar data may be of interest. For some considerations, images should be acquired at high tide, in order to delineate the land that is submerged only in exceptionally high tides. This would allow to reduce uncertainties in the visual interpretation stage, as coral reefs, sand bars and other coastal features are submerged. The coastline charted in the topographic maps is usually derived at the average high tide level and, therefore, could be directly compared with the one obtained from the images. On the other hand, radar data acquired at low tide would definitely enhance the possibility of mapping fish traps, the surface reflecting the radar beams being greater.

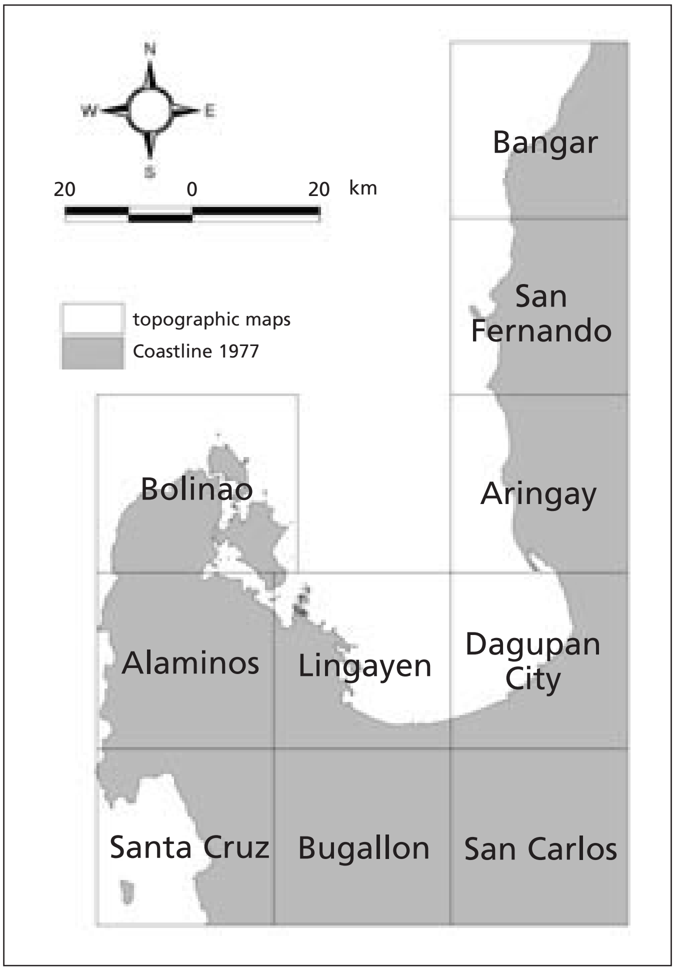
Unfortunately, the only tide measuring station in the study area is in San Fernando, which is located almost outside Lingayen Gulf. Due to the conformation of the gulf, the tidal range is greatest along the coast inside it, and particularly in its southernmost part. Thus, the tide stage cannot be derived from the records obtained in San Fernando, and consequently it has not been taken into account in the selection of the images.

Hence, the choice of the image acquisition period was based only on the season. All images were acquired in winter, during the dry season, when rice fields are not flooded. This allows to minimize the errors in the visual interpretation of the images.

The most detailed reference cartography available for the study area is a series of topographic maps at 1:50 000 scale, published in 1977. Data are mapped into the geographic system, ellipsoid Clarke 1866, datum Luzon. The study area is covered by ten topographic maps (Figure 6).

The maps were scanned and then the features of interest were digitized using the GIS software Arc View 3.2, as described in section 2.2.

FIGURE 6
Topographic maps, 1:50 000 scale, covering the study area



All the satellite images acquired for the present study were pre-processed and reprojected into the cartographic reference projection using the software Erdas IMAGINE 8.5. Satellite imagery and vector data were analysed jointly in the visual interpretation stage using the GIS software Arc View 3.2.

2.2 PREPARATION OF THE VECTOR DATABASE

The objective of the visual interpretation is to identify and map aquaculture and fisheries structures in the SAR images of the study area. These must be then compared with the cartographic data. The best strategy to perform this task is to create or transform all data in vector format, and analyse them using a GIS software.

For this reason, the first part of the preparatory work consisted in obtaining a vector database from the topographic maps of 1977, containing all the data relevant for this study. The maps were scanned at 300 dpi and the raster data thus obtained were geocoded by applying the rubber sheeting resampling procedure. This procedure puts each reference point at the given coordinates, and uses a linear interpolation to reproject the other elements of the grid. In this case, the reference points were the corners and all the grid intersections of each map. The vector information was then created by on-screen digitizing of the displayed raster maps. The scale of the topographic maps is 1:50 000, so to minimize errors the display scale for digitalization was 1:25 000 or larger.

Among the data reported on the topographic maps, only those relevant in the analysis of aquaculture and fisheries structures were digitized. Two layers were created in ArcView shapefile format, containing respectively polygons and polylines; in each case, the corresponding land cover and land use is specified by an attribute code.

The polygon layer contains the following classes:

Fishponds, empty fishponds, fishponds with nipa, and nipa

All these land use classes are directly relevant for the present study; the corresponding areas were digitized. In particular, adjacent groups of fishponds of the same category were digitized into the same polygon if they appear to be separated only by dykes, and as separate polygons otherwise.

A different code was assigned to the polygons of the four categories, as the related information might be useful in the subsequent analysis. As fishponds are periodically emptied for maintenance purposes, their being empty at the moment of the aerial survey upon which the maps are based does not necessarily imply that they were abandoned.

Regarding fishponds containing nipa palms (*Nypa fruticans,* Wurmb), this plant is extensively used as roofing material. Thus, it is sometimes grown inside fish ponds to increase their total revenue. Nipa palms emerging from water interact with the radar signal increasing the backscatter intensity over the pond surface; thus, data on their presence may be useful in the visual stage. For the same reason, nipa palms growing outside fishponds were mapped as well.

Mangroves

This land cover class is scarcely present in the study area.

Large rivers and lakes

Wide rivers can be easily identified in the SAR images. The knowledge of their boundary assists the interpreter in analysing the presence of fisheries structures inside the river itself, if its position and shape has not changed in time. In the study area, three of the largest rivers (Agno, Panto and Cayanga) actually show major modifications in the SAR data with respect to their position and extension reported in the topographic maps of 1977. The knowledge of the location and extension of natural lakes is also useful to avoid misinterpretation errors.

Actually, lakes are easily separated from fishponds as the latter are much more regular in shape and bounded by easily discerned dykes; however when the water-covered surface has a small extension, the dykes and the shape are less evident and errors may arise.

Salt pans
They cannot be separated from fishponds when they are flooded, thus knowing their location is useful to avoid interpretation errors.

Coral reefs, sand banks
Fishponds and other aquaculture structures may be built on open, shallow waters. Coral reefs have sometimes been destroyed to accommodate them, hence these areas were digitized to analyse whether this has occurred in the study area. On the contrary, sand banks are generally avoided as fishponds location because they correspond to areas where highly dynamic processes of sedimentation/erosion occur.

Mainland, islands
The coastline has been digitized as well; islands are included only if located in the open sea. The coastline on the maps corresponds to the mean lower low water. This layer has been compared with the coastline obtained from the 2001-2002 images, to enhance modifications that impacted on the location of aquaculture and fisheries structures. Digitizing of the coastline using the SAR images is described in section 2.5.

The polyline layer obtained from the topographic maps contains the following classes:

Roads and railroads
Includes the railroad and all types of roads; does not include tracks and trails. All roads have the same code. Roads and railways are relevant in the study of fishponds as they act as constraints for their expansion, facilitating at the same time fish transport to markets.

Rivers
Includes rivers whose width is too narrow to be represented in scale. The river network is an important element in the visual interpretation stage: fishponds must be connected to flowing water, and thus the ponds are always located in proximity of the main river network.

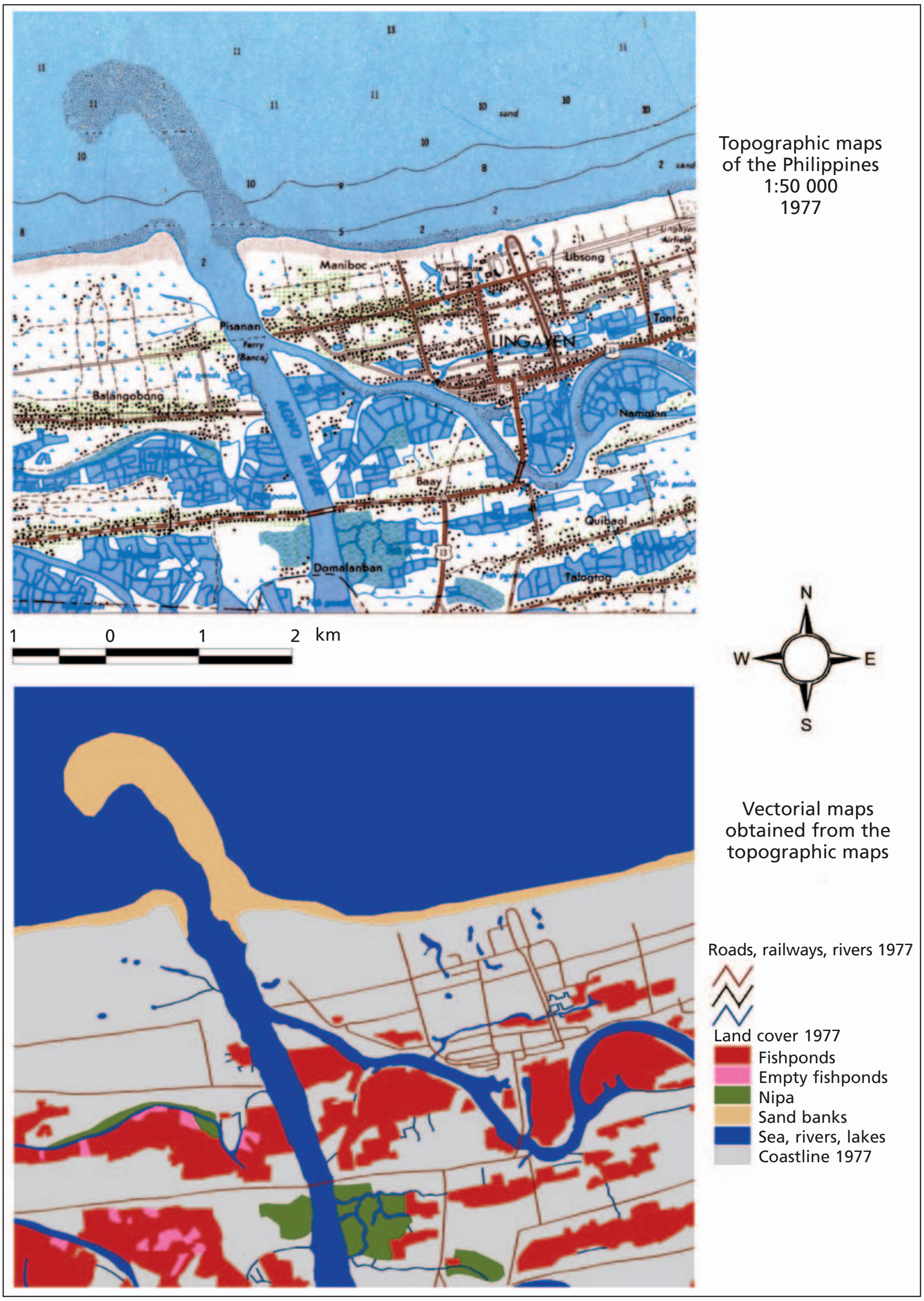
Figure 7 shows an example of the vector data obtained from the topographic maps.

2.3 MAPPING AQUACULTURE AND FISHERIES STRUCTURES BY SATELLITE IMAGING RADAR

Radar is the acronym of Radio Detection and Ranging. An imaging radar is an active device that transmits microwave pulses toward the Earth surface and measures the magnitude of the signal scattered back towards it. The return signals from different portions of the ground surface are combined to form an image. A Synthetic Aperture Radar (SAR) is a special type of imaging radar. It is a complex system that measures both the amplitude and phase of the return signals. Their analysis exploits the Doppler effect created by the motion of the spacecraft with respect to the imaged surface to achieve high ground resolution.

As the source of the electromagnetic radiation used to sense the Earth surface is the system itself, it can be operated during day and night. The atmospheric transmittance in the microwave interval used by remote sensing SAR systems is higher than 90 percent, even in the presence of ice and rain droplets (except under heavy tropical thunderstorms); thus, SAR can acquire data in all weather conditions.

FIGURE 7
A portion of Dagupan City topographic map (sheet 7074 II) and the derived vector data



A drawback of SAR imaging is the presence of noise (speckle) in the images. The noise is created by constructive and destructive interference between the backscattered energy from different portions of the ground surface included in the same cell (pixel) of the SAR image. The value of the pixel is thus increased or decreased; the SAR image appears to be covered by randomly scattered bright and dark spots.

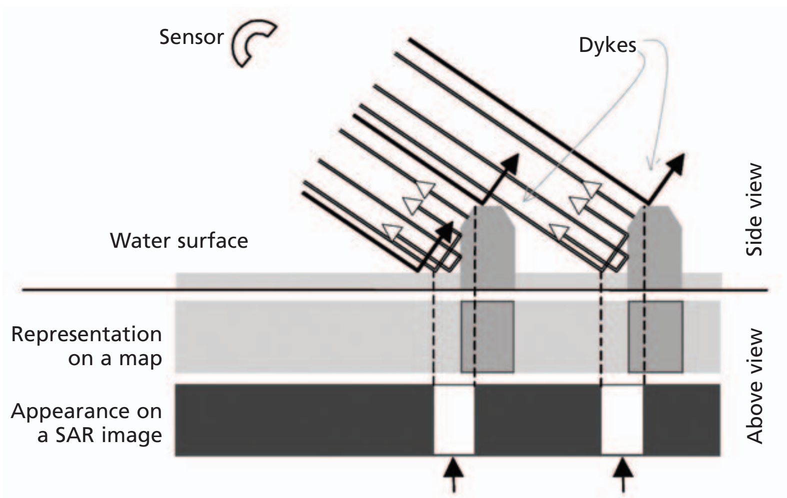
In all satellite imaging SAR systems, the pulses are emitted sideways, downwards to the Earth's surface and perpendicularly to the flight direction. The ERS SAR acquires strips of imagery approximately 100 km wide, 250 km to the right of the sub-satellite track; the incidence angle of the emitted pulses in the middle of the imaged stripe is 23°, and the ground resolution is of 12.5 x 12.5 m.

The SAR on board RADARSAT operates in several acquisition modes, obtaining images with varying resolution and size. To detect aquaculture and fisheries structures the highest possible resolution is necessary; this corresponds to the Fine Resolution acquisition mode. The ground resolution is 6.25 m; the acquired image is 50 km wide, it is located 385 km to the right of the sub-satellite track, and its mid-image incidence angle is of 44.259°.

Aquaculture structures are evident in SAR data because their components influence in a peculiar way the radar backscatter.

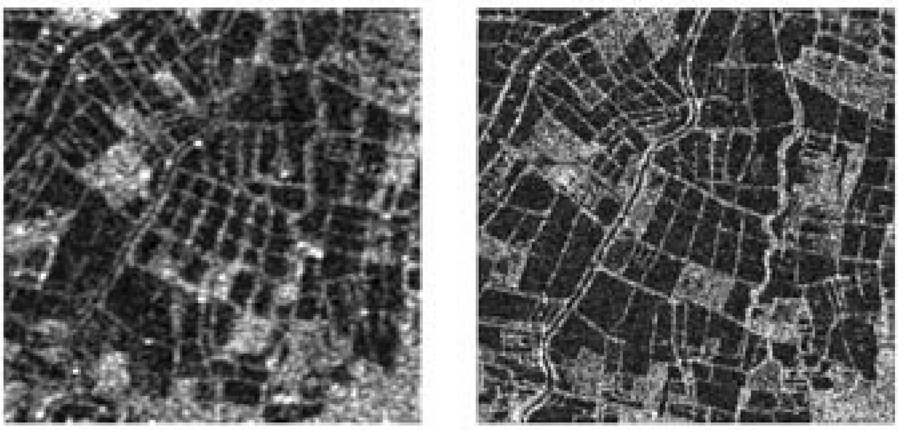
An analysis of fishpond appearance on SAR data has already been conducted by Travaglia, Kapetsky and Profeti (1999). Fishponds are small enclaves of calm water surrounded by dykes on all sides. A dyke is an earthen wall whose thickness ranges approximately from half a metre to several metres, and whose elevation from the water surface is at the most a metre. While a calm water surface behaves like a specular reflector, sending only a small part of the signal back to the sensor, a dyke reflects back a large amount of the incoming energy, because its sides intersect the surrounding water at approximately a right angle, creating a "corner reflector" (Figure 8).

FIGURE 8
Interaction of radar beams with dykes and water surfaces on a group of fishponds



The position of the dykes in the image is shifted along the cross-track direction and toward the sensor. The apparent dimensions of the dykes in the image do not correspond to the real ones.

Appearance of fishponds in the ERS-2 SAR image of 2 December 2002 (left) and in the RADARSAT-1 SAR image of 4 February 2001 (right)

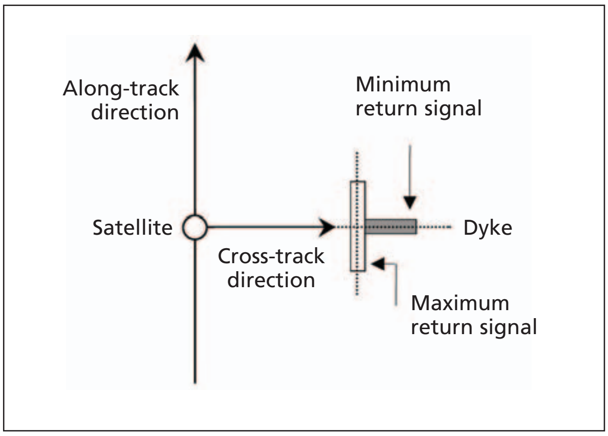


As shown in the figure, the radar signal bounces off of both planar surfaces and is reflected directly back toward the antenna. The pixel corresponding to the corner reflector has a high value, and thus fishponds appear as dark areas surrounded by bright, elongated structures.

Due to the peculiar acquisition geometry, the position of a corner reflector in a SAR image does not correspond exactly to the orthogonal projection of the dykes on a map. The position of the dykes in the image is shifted along the scanning (cross-track) direction and toward the sensor, and their apparent extension does not correspond to the actual one. Actually, the SAR signal of each pixel is obtained by averaging the radiation reflected back by the various surfaces inside the area corresponding to the pixel. Thus, if the imaged area contains a small but highly reflective object, the average backscattered radiation is almost equal to the single contribution of the object. As a result, the pixel assumes a high value and the dyke appears to be as big as the entire pixel. The multiple reflection on the dyke may also spread the high return signal to the surrounding pixels, increasing their values as well. Therefore, the extension of a dyke may appear larger in a SAR image than in reality.

The return signal of elongated objects varies also as a function of the angle between the object and the cross-track direction (Figure 9). Surface features oriented in a parallel way with respect to the scanning direction are less evident than those oriented perpendicularly to the scanning direction. Hence, if a dyke is parallel to the cross-track direction, it may escape detection.

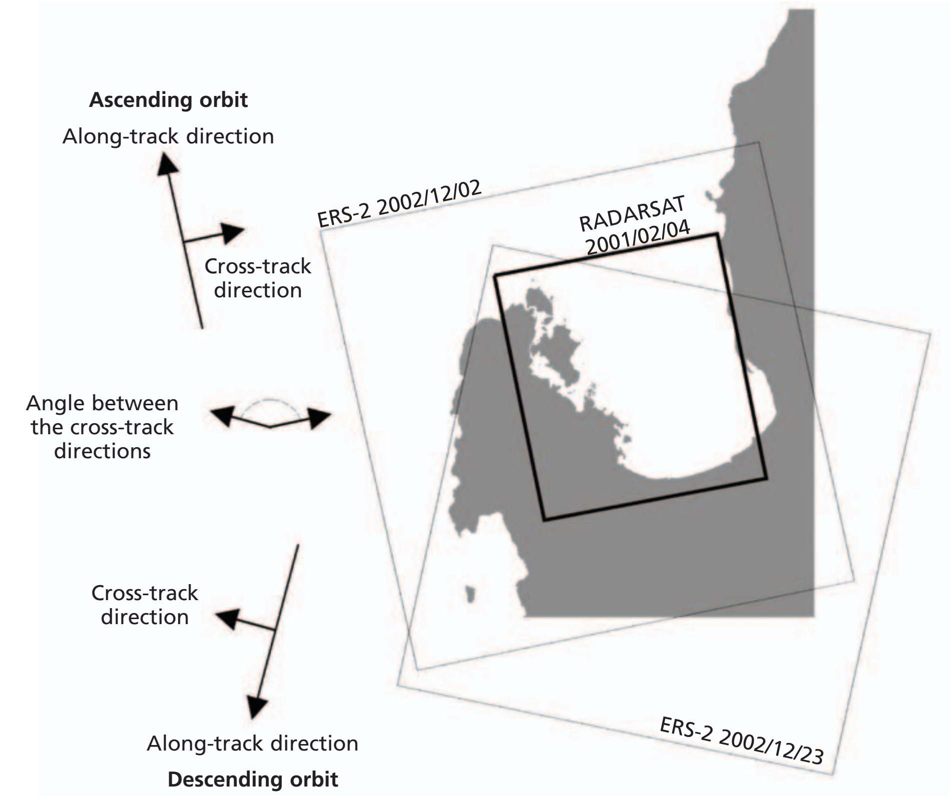
FIGURE 9
Return signal as a function of the angle between a dyke and the cross-track direction



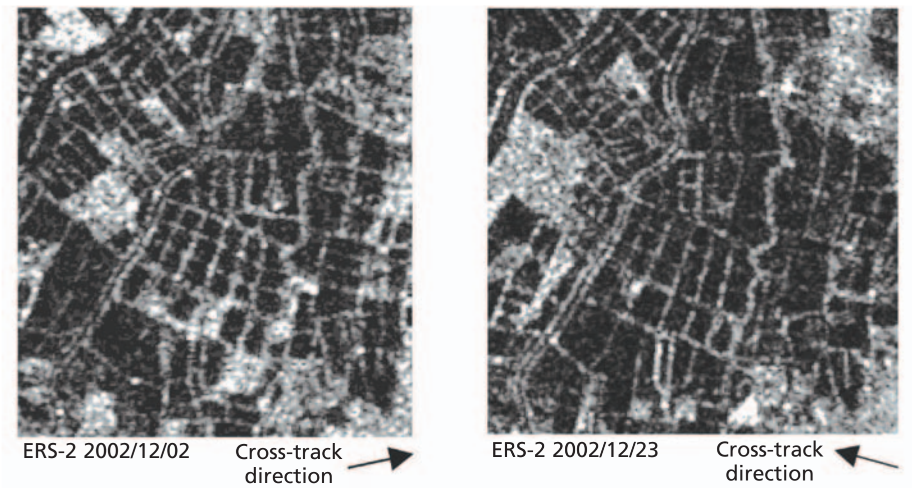
The ERS-2 satellite follows a quasi-polar orbit, and as described previously its scanning direction (or *cross-track* direction) is right of the sub-satellite track. Thus, in descending orbits (from the North Pole downwards) the scanning direction is approximately opposite to that in ascending orbits (Figure 10). Consequently, surface features are highlighted in a different, complementary way on a pair of images acquired respectively in ascending and descending orbits.

The angle between the scanning direction of the two ERS SAR images used in this study is of 152.708 degrees. A comparative analysis of both images allows to identify properly all features, if they are acquired at a short time interval in order to minimize changes over the imaged surfaces between the two acquisitions.

FIGURE 10
The angle between the scanning directions in the SAR data used in the study



Differences in the fishpond pattern due to the diverse scanning directions in the ERS SAR images acquired on ascending and descending orbits

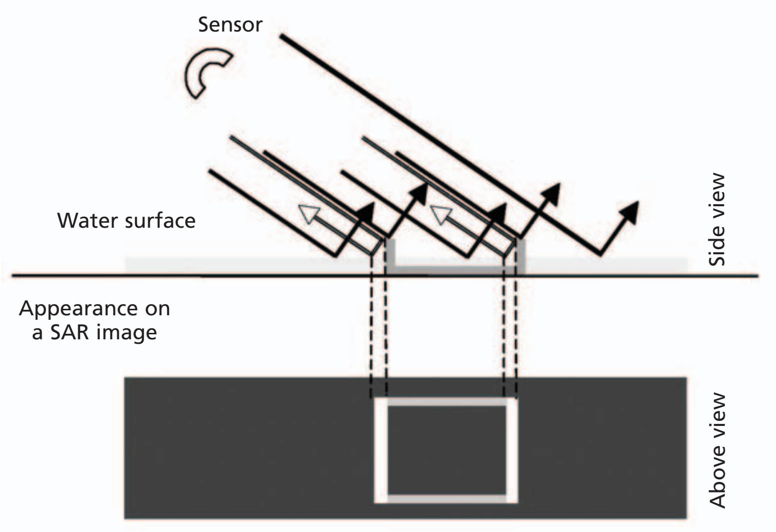


The other aquaculture and fisheries structures influence the radar signal in a similar way. The vertical sides of fish cages, pens and traps, emerging from the water surface, create the corner reflector effect that allows to identify them. For example, Figure 11 shows the interaction of SAR pulses with a fish cage. The sides of the cage oriented perpendicularly to the scanning direction are brighter in the SAR image.

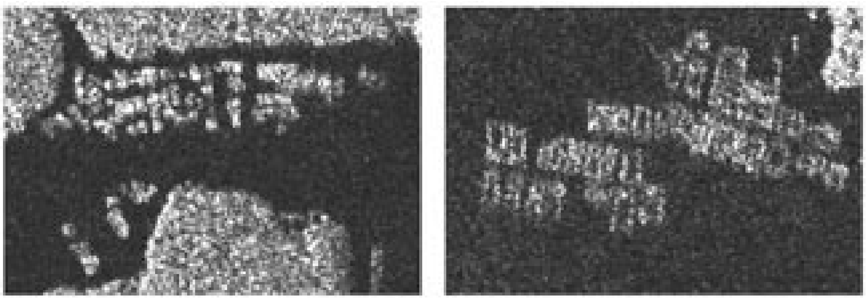
In the smaller cages, the extension of the water surface inside is very small with respect to the sensor resolution and may not be represented in the image. As a result, the cage will appear as a bright group of pixels on the dark sea surface (Figure 12). The same happens to the smaller fish pens.

Both ERS and RADARSAT SAR sensors operate in the C-band (frequency 5.3 GHz, wavelength 5.6 cm). A SAR system generally sends out either horizontally (H) or vertically (V) polarized pulses, and collects either horizontally or vertically polarized return signals. The ERS SAR sends and receives vertically polarized signals (VV), while RADARSAT SAR sends and receives horizontally polarized signals (HH). Thus, both these sensors measure the portion of the backscattered signal which has maintained the original polarization.

FIGURE 11
Interactions of radar beams with a fish cage



Appearance of small cages (left) and large cages (right) in a RADARSAT-1 image



The differences in the appearance of various coastal land features, including fishponds, on ERS and RADARSAT imagery were studied by Paringit *et al.* (1998) on the area of the Panay-Guimaras Strait (the Philippines) using the airborne NASA/JPL AirSAR polarimetric system. Their results show that the mean backscattering coefficient of fishponds is slightly higher on C-band images acquired in VV polarization than in HH. VV data are, however, more sensitive to sea surface roughness (Touzi, 1999) which in turn depends on wind speed. Wind speeds greater than approximately 1.5 m/s (Fingas and Brown, 2000) create waves that increase the return signal intensity in C-band, diminishing the contrast among sea surface and the structures located offshore. The contrast keeps diminishing as the wind speed becomes more intense. This effect is clearly shown in Figure 12.

Fish cages are evident in the RADARSAT-1 image and in the first ERS image (of 2 December 2002); they are barely visible in the second ERS image (of 23 December 2002) due to the increased sea surface roughness. It should be noted that in the second ERS image the coastline appears different, as the image was acquired during the receding tide; the emerging coral reefs contribute to increase sea surface roughness, thus reducing the possibilities of detecting fisheries structures.

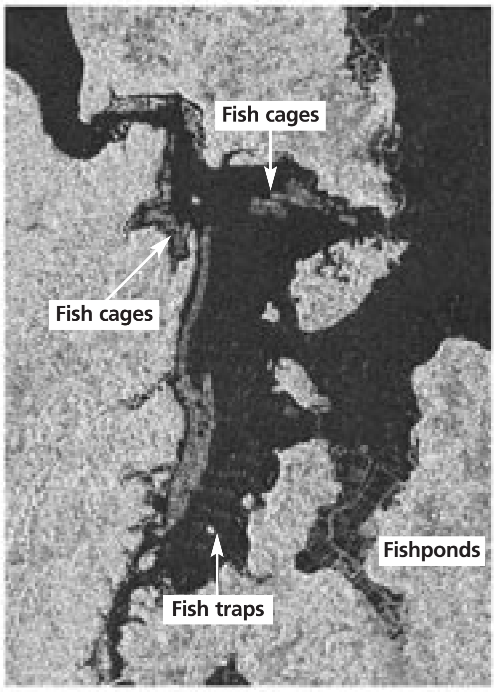
Finally, the appearance of the structures in the SAR imagery is also greatly influenced by the spatial resolution of the sensor. Fisheries structures are generally made out of thin components and cover limited extensions; thus, the highest the spatial resolution the higher the possibility of detecting them. In particular, the smaller fish pens may not be evident in ERS SAR images, and fish traps are generally too thin to be detected; they appear only in the higher-resolution RADARSAT image (Figure 12).

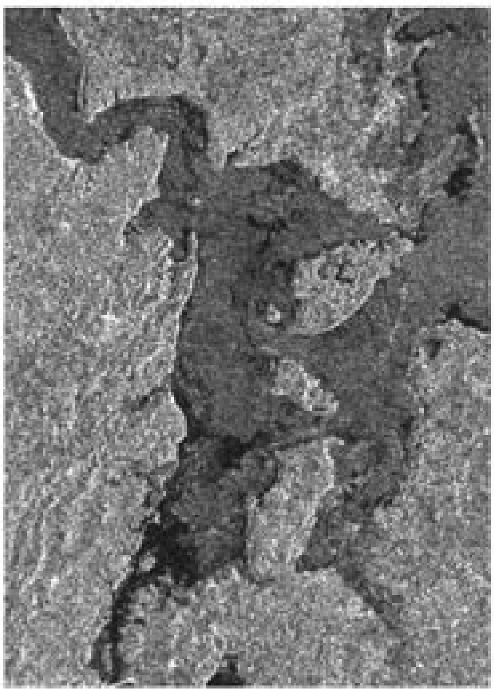
FIGURE 12
Sea state and coastal aquaculture and fisheries structures mapping

Upper right: RADARSAT-1 image acquired on 4 February 2001. Sea surface roughness is low, and the contrast with the bright structures of fishponds, cages and traps allows to identify them easily.

Lower left: ERS-2 image acquired on 2 December 2002. Areas of rough sea surface are evident in the image. In these areas, the contrast between sea surface and fishing structures is lower.

Lower right: ERS-2 image acquired on 23 December, 2002. This image has been acquired under low tide and high sea surface roughness; consequently, offshore fishing structures are barely evident.





The visual interpretation procedures used to map coastal aquaculture and fisheries structures are described in section 2.6.

2.4 IMAGE PRE-PROCESSING PROCEDURE

In order to perform the visual interpretation of the SAR images, they must all be geocoded in the same projection of the reference cartography. Speckle-reducing filters also were applied to the images to verify whether it was possible to enhance their interpretability.

The SAR images were provided already geocoded: the ERS-2 projected into UTM/WGS 84, and the RADARSAT-1 into geographic/WGS72, as described in section 2.1. The reference cartography was represented into geographic/Clarke 1866, thus all the images were reprojected into geographic/Clarke 1866 so that they could be overlaid with one another and with the cartography.

The automatic reprojection procedures provided by the Erdas IMAGINE software were applied at first, but when the images generated by these procedures were overlaid on the cartography they showed consistent misplacements. It has thus been necessary to manually geocode each image, using the "non-linear rubber sheeting" procedure. This method is based on the identification, over the image and over the cartography, of a large number of ground control points (GCPs). The coordinates of each pixel on the new geocoded image are then obtained interpolating nonlinearly the coordinates of the surrounding reference points. All the three SAR images were geocoded using more than four hundred GCPs, reaching a RMS error lower than 1.5 pixels; the output pixel size is 0.00005825 decimal degrees, equivalent to 6.25 m.

SAR images are affected by the presence of noise (speckle), created by constructive and destructive interference between the backscattered energy from different portions of the ground surface included in the same pixel of the SAR image. The value of the affected pixels is thus increased or decreased; the SAR image appears to be covered by randomly scattered bright and dark spots.

Thus, to complete the image preparation, it may be useful to apply speckle reducing procedures to the SAR images in order to increase their interpretability.

A simple, yet useful technique has been tested by Profeti, Travaglia and Carlà (2003) on multi-temporal SAR data to improve the visual interpretation of fish ponds. This technique enhances time-invariant spatial features and reduces speckle, without compromising the geometrical resolution of the images. This method allowed to obtain good results; however, it can be applied only on multiple images of the same area acquired by the same sensor in the same acquisition geometry, while in this study the two ERS-2 images were acquired in ascending and descending orbits; therefore, it is not applicable in this case.

The most common speckle removal procedures are based on adaptive spatial filtering based on local statistics. The filters analyse each pixel's contextual information and produce a new image in which the value of each pixel is obtained from the values of its neighbouring pixels in the original image. Regardless of the specific filtering technique, noise reduction is achieved at the expense of the geometric detail of the image. Several filters proposed in literature (Lee, 1980 and 1981; Frost *et al.,*1982; Li, 1988) were tested upon each type of fisheries structure to be identified in the image, to evaluate their effectiveness in improving the structures' visual appearance.

The analysis of the results shows that the original images are sharper and richer in details, very useful for visual interpretation purposes. Consequently, no speckle removal filters were applied.

2.5 DIGITALIZATION OF THE SHORELINE

Differences among the shoreline profile can be observed between the two ERS-2 images. On the first (acquired on 2 December 2002), the emerged land is wider than on the second (acquired on 23 December 2002) and part of the coral reef is also visible. The difference between land and water among the RADARSAT and the second ERS-2 image is small, and is probably more related to scale difference and geocoding than to tide stage.

At present, several different shoreline definitions are in use by various state and local authorities. The U.S. National Oceanic and Atmospheric Administration

(NOAA) has adopted as standard shoreline the approximate line where the average high tide, known as Mean High Water (MHW), intersects the coast. In our case, the Philippines topographic maps use the Mean Lower Low Water (MLLW).

As no information on tides was available for the study area, it has not been possible to acquire images in a determined tide stage. Thus, it was decided to delineate the coastline by visual interpretation, using the image in which the coastline was more evident. To decide which image was best suited to be the reference for shoreline mapping, the scientific literature on this subject was reviewed. The use of airborne and spaceborne SAR imagery to delineate land boundaries has been tested widely in the last years; for example, RADARSAT imagery has been used to map the coastline on behalf the Digital Marine Resource Mapping (DMRM) program, initiated by the Government of Indonesia in 1996 (Hesselmans *et al.,* 2000). A wider scientific research on the use of new technologies for shoreline mapping is being conducted by NOAA and the U.S. National Geodetic Survey on behalf the Coastal Mapping Program. It includes experiments on the use of satellite SAR imagery, whose results show that RADARSAT fine mode (HH) enables to map the coastline within 28 m and at 98 percent confidence level with respect to shoreline data produced using conventional photogrammetric processes (Tuell, Lucas and Graham, 1999). Other sources confirmed that HH imagery is better suited for shoreline mapping than VV imagery (although quadpol image data are considered to be the most suitable at all).

Therefore, the RADARSAT fine mode image has been used to map the coastline in the small portion of the study area it covers (Figure 2). The ERS-2 image acquired on 23 December 2002 has been used to complete the coastline at high tide, while the other ERS-2 SAR image (of 2 December 2002) has been used to map the low-tide boundary.

To map the low-tide coastline, the second ERS-2 image was overlaid with the land/sea boundary at high tide. Whenever the differences were wider than two pixels, they were mapped; this limit distance has been assumed sufficient for compensating geocoding errors and positioning errors related to the different scanning direction.

2.6 MAPPING PROCEDURES

The description of the appearance of aquaculture and fisheries structures in SAR images, outlined in the previous sections, was used in the visual interpretation of the images.

The visual interpretation was performed using the Arc View software, as it is more suited for on-screen digitizing of the boundaries of the features. Two vector layers were created in order to collect the polygons and polylines of the classes of interest. Their content is described respectively in Tables 4a and 4b.

Polygons and polylines were digitized in the cartographic reference projection of the Philippines (section 2.1).

TABLE 4a
Classes identified in the SAR images: Polygon layer

Class Name	Notes
Salt pans 2002	No apparent changes from the extension mapped in 1977
Fishponds 2001 and 2002	Identified both on RADARSAT-1 and on the two ERS images
Fishponds 2001 and 2002, uncertain	Identified on one image only, out of two or three (where available)
Fish pens 2001	Identified on RADARSAT-1 data
Fish pens, uncertain	No assignments to this class
Fish cages 2001	Identified on the RADARSAT-1 image
Fish cages 2001, uncertain	May be a small island or a rough patch in the sea surface
Fish cages 2002	Identified on the ERS-2 images
Fish cages 2002, uncertain	May be a small island or a rough patch in the sea surface
Areas with fish traps in the open sea 2001	Polygons drawn around the areas on which fish traps were detected, to have an approximate estimation of their extension
Areas with fish traps inside rivers 2001	
Mainland, high tide	Coastline at high tide, obtained from RADARSAT-1 (2001/02/04) and the ERS-2 image acquired on 2002/12/02
Islands (open sea)	Islands inside the major rivers are not included

For each element located in the images, the following parameters were calculated:
– Polygons: area (km^2) and perimeter (km);
– Polylines: length (km).

The global area or length of the elements in each class have then been calculated and compared with the available ground truth from the topographic maps. The results are described in Chapter 3.

TABLE 4b
Classes identified in the SAR images: Polyline layer

Class Name	Notes
Traps in the open sea	Each line has been drawn on the segments composing the arrow-like traps, if detectable. Their length is thus an underestimation of the real value
Traps inside rivers	
Mainland + reef, low tide	Dry land at low tide, added to the “Mainland, high tide” class; it may include portions of the reef. Obtained from the ERS-2 image of 2002/12/23. Note that the image allows to recognize the coastline only on certain portions of the study area; thus, this class’ polygons do not represent a complete map

3. Results

The results obtained by the visual interpretation of the SAR images and the comparison with the data obtained from the topographic maps of 1977 are reported in this chapter. Results refer to the area under study, that is the area covered by the satellite frames, and to the period of acquisition of the satellite data.

Table 5 shows the total area covered by the features of interest in the entire study area. This include various types of aquaculture and fisheries structures, plus the salt pans.

TABLE 5
Total area covered by the classes of interest (Pangasinan province)

Class Description	Number of Units	Total Area (km^2)
Salt pans 2002	1	4.156
Fishponds 2002	587	157.723
Fishponds 2002, uncertain[1]	33	2.036
Fish pens 2001	22	1.600
Fish cages 2001	105	2.439
Fish cages 2001, uncertain[2]	7	0.054
Fish cages 2002	267	1.390
Fish cages 2002, uncertain[2]	16	0.019
Areas with fish traps in the open sea 2001[3]	12	18.943
Areas with fish traps inside rivers 2001[3]	6	1.703

[1] Identified in one image only, out of two or three.
[2] Uncertain assignment: may be a small island or a rough patch in the sea surface.
[3] Polygons drawn around the areas on which fish traps were detected, to have an estimate of their extension.

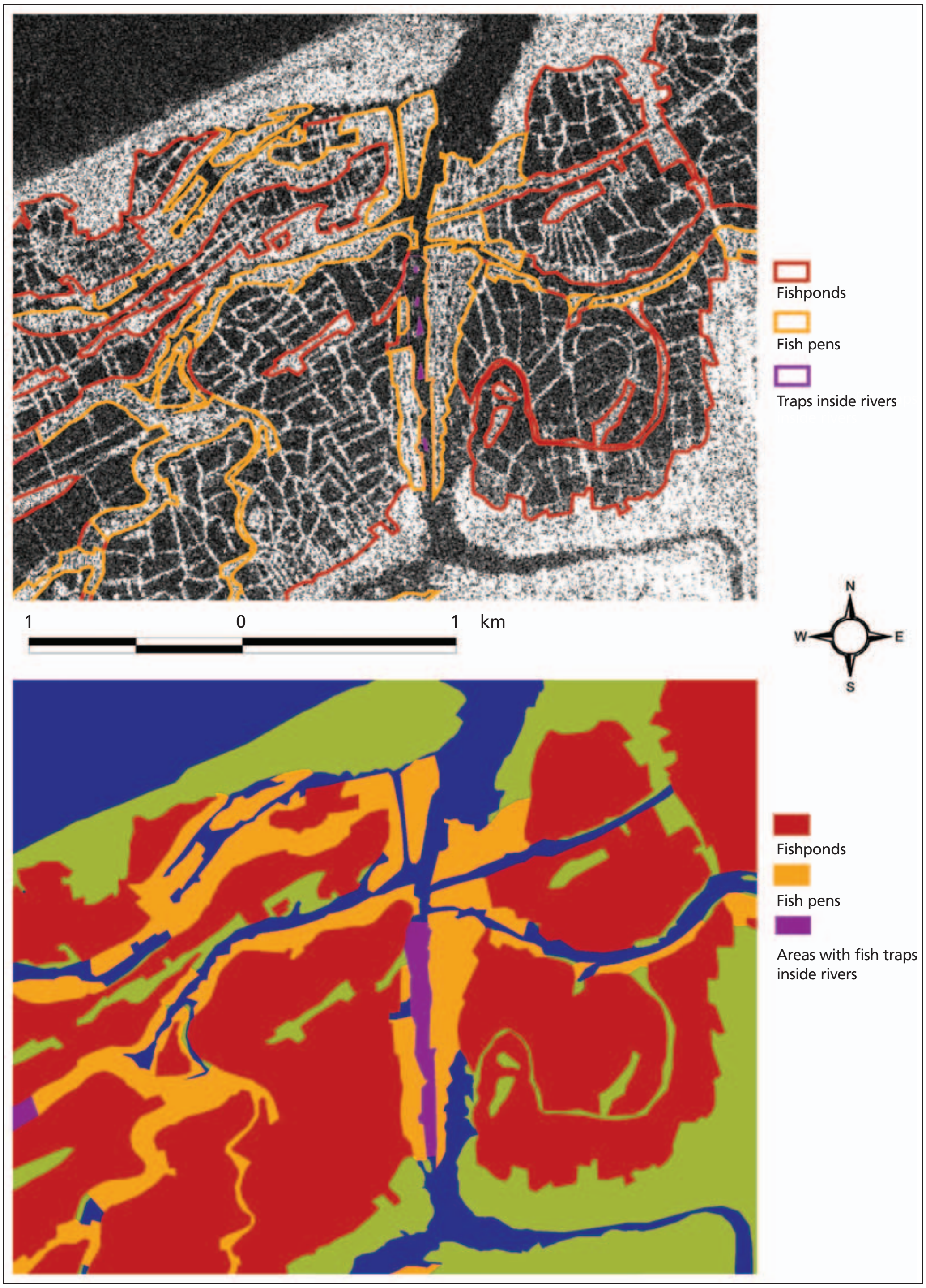
The study area covers completely the Pangasinan province, plus approximately two–thirds of La Union and a small portion of Zambales provinces. All mapped aquaculture and fisheries structures occur in the Pangasinan province only, with the exception of some fishponds (90 units covering 18.762 km^2) and of some fishponds classified as uncertain (13 units covering 2.613 km^2) existing in the other two provinces.

Table 6 summarizes the statistics on fish traps. These include all the segments composing the arrow-like traps, if detectable. The results obtained for each type of fisheries structure are presented in the next sections.

TABLE 6
Length of the fish traps detected in the study area

Class Description	Number of elements	Cumulative length (km)	Average length (km)	Minimum length (km)	Maximum length (km)	Standard deviation
Traps in the open sea	378	50.104	0.133	0.018	0.642	0.093
Traps inside rivers	84	7.886	0.094	0.024	0.364	0.061

FIGURE 13
Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures



3.1 FISHPONDS

Fishponds occupy the largest surface of all the structures occurring in the area. It is interesting to compare the surface occupied by fishponds in the year 2002 (excluding the class fishponds – uncertain) with their area coverage mapped in the 1977 cartography.

The cartography showed three types of fishponds: active, empty, and active containing nipa (section 2.2). Fishponds are routinely emptied for maintenance purposes, and nipa trees are cultivated inside active fishponds; thus, in order to perform a correct comparison, the cumulative surface covered by these three classes in the cartography of 1977 has been calculated.

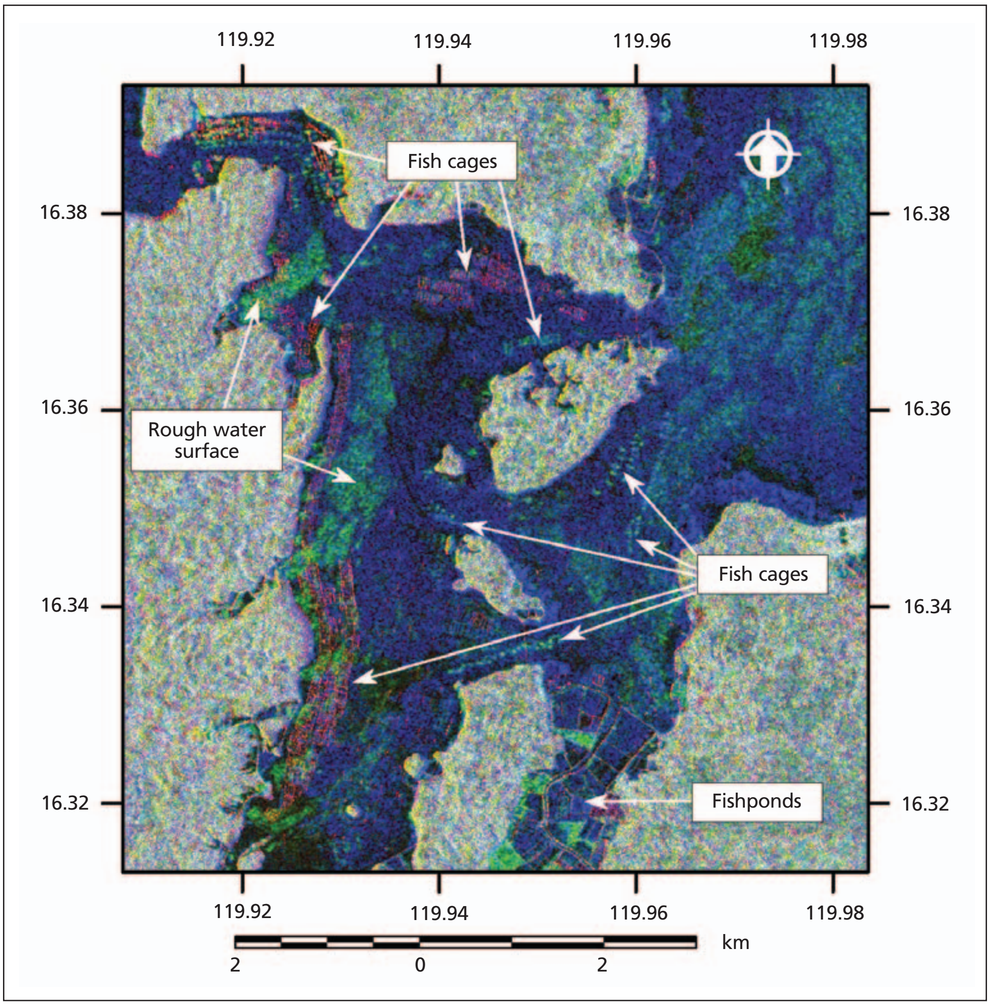
The results are shown in Table 7: the cumulative area occupied by fishponds has increased. It must be noted that this does not correspond to a simple expansion of the fishponds existing in 1977. Some of the ponds mapped in 1977 were converted to other uses (e.g. commercial lots).

Fishponds appear in SAR images as shown in Figures 8 and 13.

TABLE 7
Comparison between the fishponds area coverage in 1977 and in 2002

	Total Number of elements	Cumulative area *(km²)*
Fishponds 1977	640	110.248
Fishponds 2002	677	176.485
Difference	+ 37	+ 66.233

FIGURE 14
Colour combination of the three SAR images used in the study. Red: RADARSAT-1, 4 February 2001; green: ERS-2, 2 December 2002; blue: ERS-2, 23 December 2002
(Note the different position of fish cages in 2001 and 2002)



3.2 FISH PENS

Fish pens were detected only on RADARSAT-1 data, as explained in the preceeding chapter. The pens are located in the estuaries of the major rivers. In many cases, they are adjacent to fishponds.

The 1977 cartography does not include fish pens, thus a comparison with the actual position and location is not possible. Figure 13 shows the typical appearance of fish pens on SAR images.

3.3 FISH CAGES

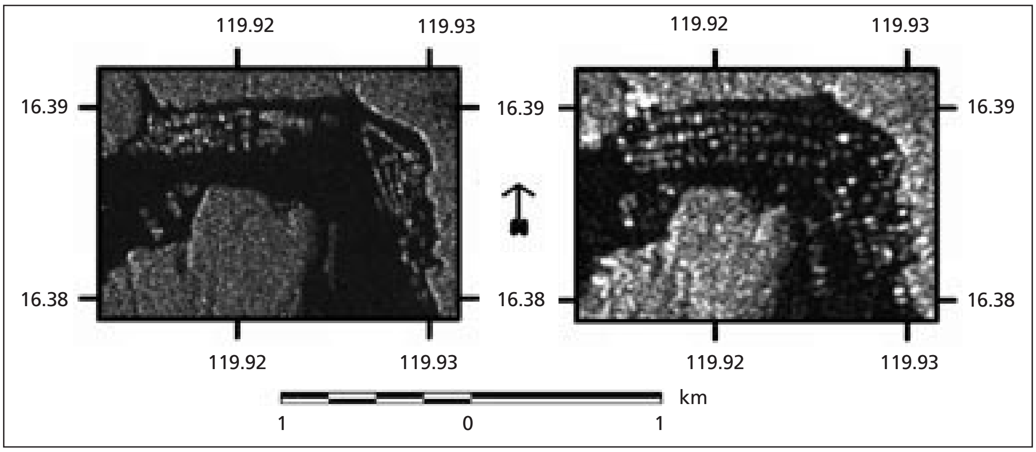
Fish cages were detected both on the RADARSAT-1 image of 4 February 2001 and in the two ERS-2 images of 2002. They are more evident in the first ERS-2 image (2 December 2002), as in the second one (23 December 2002) the roughness of the sea surface and the low tide decreased the contrast between cages and the surrounding surfaces (Figure 14). Table 5 lists the number of elements (cages or groups of cages) found by visual interpretation of the RADARSAT-1 and ERS-2 images, and the corresponding total surface. The number of cages detected in the ERS-2 images of 2002 is greater than in the RADARSAT-1 image of 2001. However, the total surface of the cages in 2002 is smaller than in 2001. In fact, more small cages and less large cages were detected in the 2002 images with respect to the 2001 images.

Fish cages may be of several shapes (square, rectangular, circular) and of various materials. Those made up mainly of metal have a brighter appearance on SAR images. In fact, in addition to the factors described in section 2.2, the intensity of the SAR backscattered signal is proportional to the dielectric constant of the scattering surface; metals have high dielectric constants and generate a stronger return signal.

Figure 15 shows the appearance on RADARSAT-1 SAR and ERS-2 data of small metallic and non-metallic fish cages. Figure 16 shows the appearance of large cages on RADARSAT-1 SAR data.

Data on fish cages in 1977 are not available, thus a comparison with the actual area coverage and location is not possible.

FIGURE 15
Appearance on RADARSAT-1 (left) and ERS-2 (right) images of small metallic and non-metallic fish cages. Metallic cages appear as brighter spots



3.4 FISH TRAPS

Fish traps were separated into two categories: offshore traps and traps inside major rivers. The areas occupied by fish traps were contoured only approximately to estimate their extension. Traps were detected only on RADARSAT-1 data of 2001.

Table 6 shows the statistics obtained from the polylines digitized from the detected traps. These data are not precise, as in many cases only the central structure of the traps is visible in the images; on the other hand, because of their dimensions (section 2.2) the uncertainty on the identification of traps is higher than that of the other structures. Figure 17 and 18 show respectively the typical appearance of offshore traps and traps inside major rivers on RADARSAT-1 SAR images. Traps were not mapped in the cartography of 1977, thus a comparison with the past situation is not possible.

FIGURE 16
Appearance of large fish cages on RADARSAT-1 SAR data

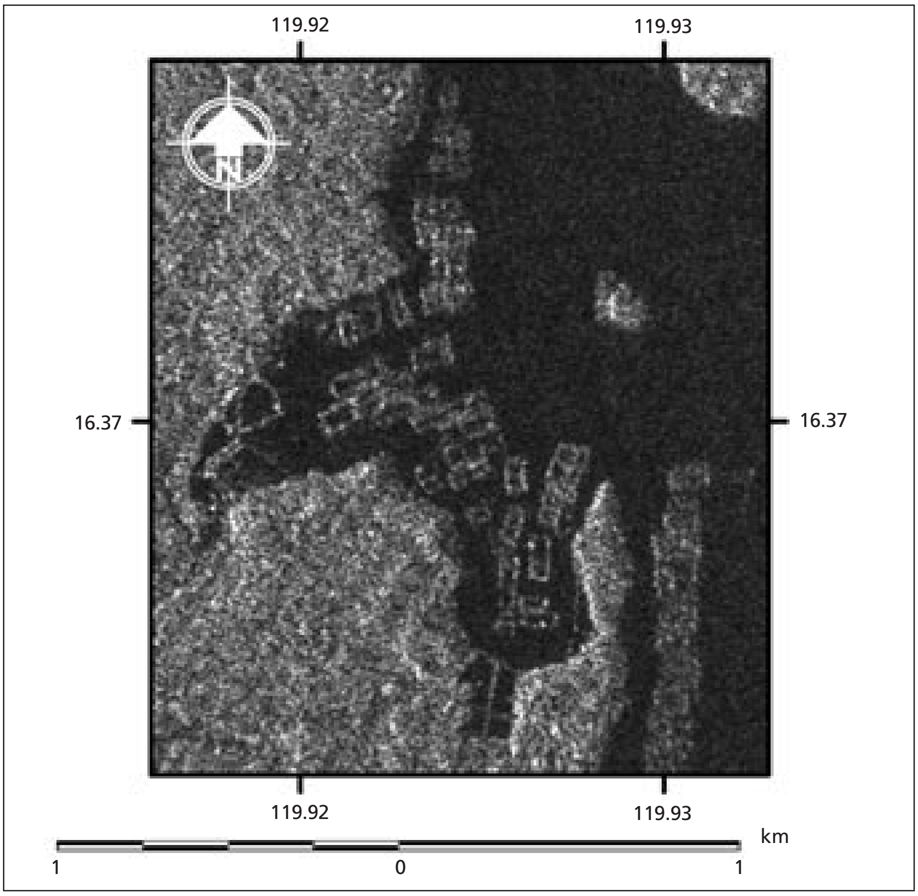


FIGURE 17
Appearance of offshore fish traps on the RADARSAT-1 SAR image

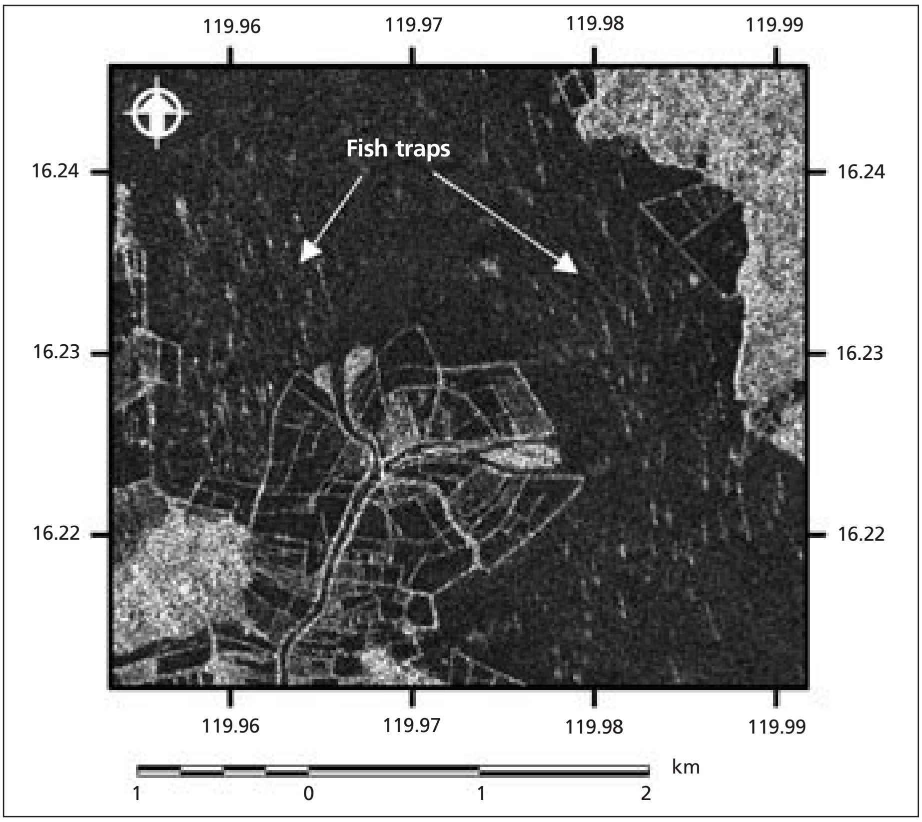
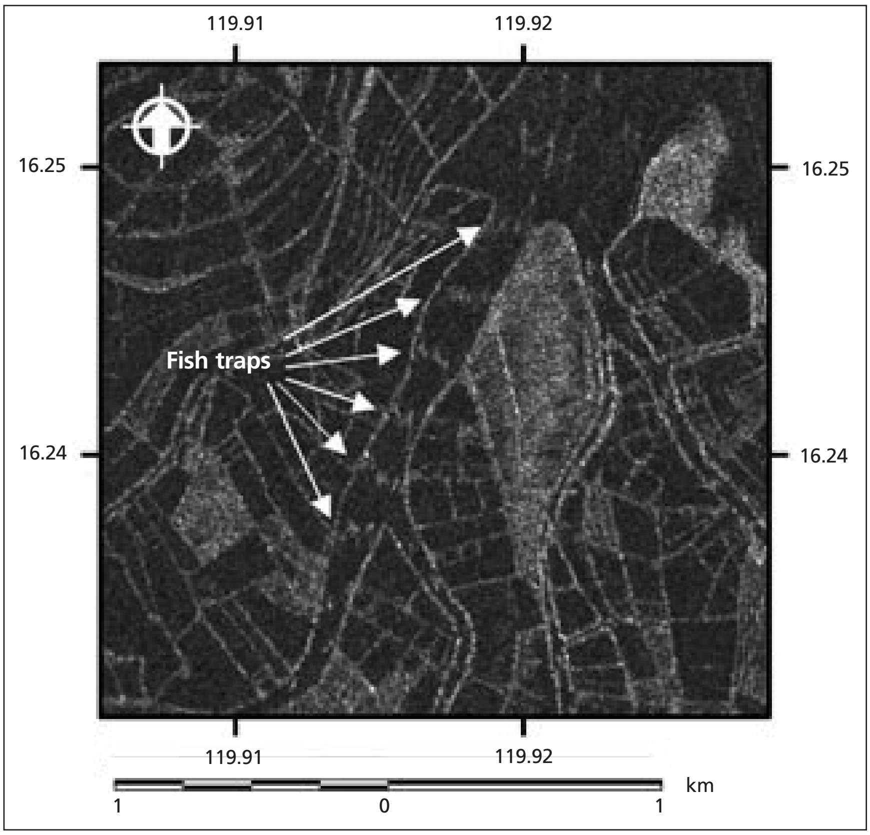


FIGURE 18
Appearance of fish traps inside rivers on the RADARSAT-1 SAR image



3.5 LAND COVER CHANGES

By comparing the results of the SAR mapping with the 1977 cartography, some interesting observations can be made.

The 58.2 percent of the present fishponds occupy areas which were already devoted to aquaculture in 1977. The new fishponds (31.5 percent) are mainly located on former agricultural land.

In contrast, only 6 percent of the land covered by fishponds in 1977 has now a different use. This can also be a direct consequence of the evolution between 1977 and 2002 of the drainage network, the major rivers having noticeably changed their course with subsequent flooding and siltation phenomena.

3.6 FIELD VERIFICATION EXERCISE

A team of the BFAR went in December 2003 to Lingayen Gulf to check the accuracy of the mapping results. They were equipped with all the necessary tools (GPS, compass, digital cameras, topographic maps and SAR mapping results at 1:50 000 scale) and checked the interpretation of SAR images. Before discussing the field validation results, the following aspects of the work should be considered:

1. Fish traps were recognized only on RADARSAT data which were acquired on February 2001, that is about two years before the field check. Some of them could have been removed or moved somewhere else in this timeframe;
2. Fish cages were easily mapped with both RADARSAT-1 and ERS-2 data. As the cages are floating, they can be moved to other places if there is a need. Actually, a group of cages located between Luzon Island, Santiago Island and Cabarruyan Island presents two distinct locations in RADARSAT-1 (February 2001) and in ERS-2 (December 2002), most probably as a consequence of a typhoon (Figure 14). Thus the field checking of fish cages was limited to ascertaining the presence of fish cages in the vicinity of the place indicated in our SAR-derived maps, as in a one year

interval the cages could have been moved somewhat. However, in the majority of the cases, the fish cages were still at the places mapped from radar data.

3. Fish pens and fishponds, being semipermanent structures, were not influenced by the one year time interval and thus they were field checked at the exact coordinates reported in the radar-derived maps. In limited cases fishponds were converted to other uses in the most recent months, but interviews with local people confirmed their original nature.

The field work was thus aimed at mainly verifying the interpretation of fishponds and fish pens. The survey was conducted on 32 verification points, selected by means of a two-stage cluster sampling scheme (Figure 19). Some verification points were also located on the "fishponds, uncertain" class, as the results could have assisted in fine-tuning the interpretation keys. The results of the ground truth on the verification points and the corresponding visual interpretation are described in Table 8.

The ground verification included also six observation points located offshore and inside rivers, in order to confirm the presence of fish cages and traps in/or the proximity of the points in which they are located in the SAR images.

The analysis of the ground truth at the verification points shows that both the two points located on the class "fishponds, uncertain" are in fact other types of water-covered surfaces. This confirms the correctness of the main interpretation key, according to which the water-covered surfaces were assigned to the class fishponds only if the surrounding dykes were visible. Water-covered surfaces regular in shape but not surrounded by visible dykes were assigned to the class "fishponds, uncertain"; the results of the ground survey demonstrate that the class "fishponds, uncertain" should be removed from the final map.

Of the other 30 verification points, 23 are located on areas interpreted as fishponds, four on fish pens and three on salt pans. The actual land use was different at one point only; it had been assigned to fishponds by the visual interpretation, but the corresponding area is a marshland bordering salt pans.

The user's accuracy of the verified classes, e.g. the ratio between the total number of points truly belonging to a class and the total number of points assigned to the same class by the visual interpretation procedure, is thus 100 percent for salt pans and fish pens, and 95.7 percent for fishponds. These figures give the probability that a point on the interpretation map truly corresponds to the class to which it has been assigned. However, the actual accuracy of the "salt pans" class might be lower, due to the fact that they may appear very similar to fishponds when they are completely flooded.

FIGURE 19
Position of the verification points and of some observation points

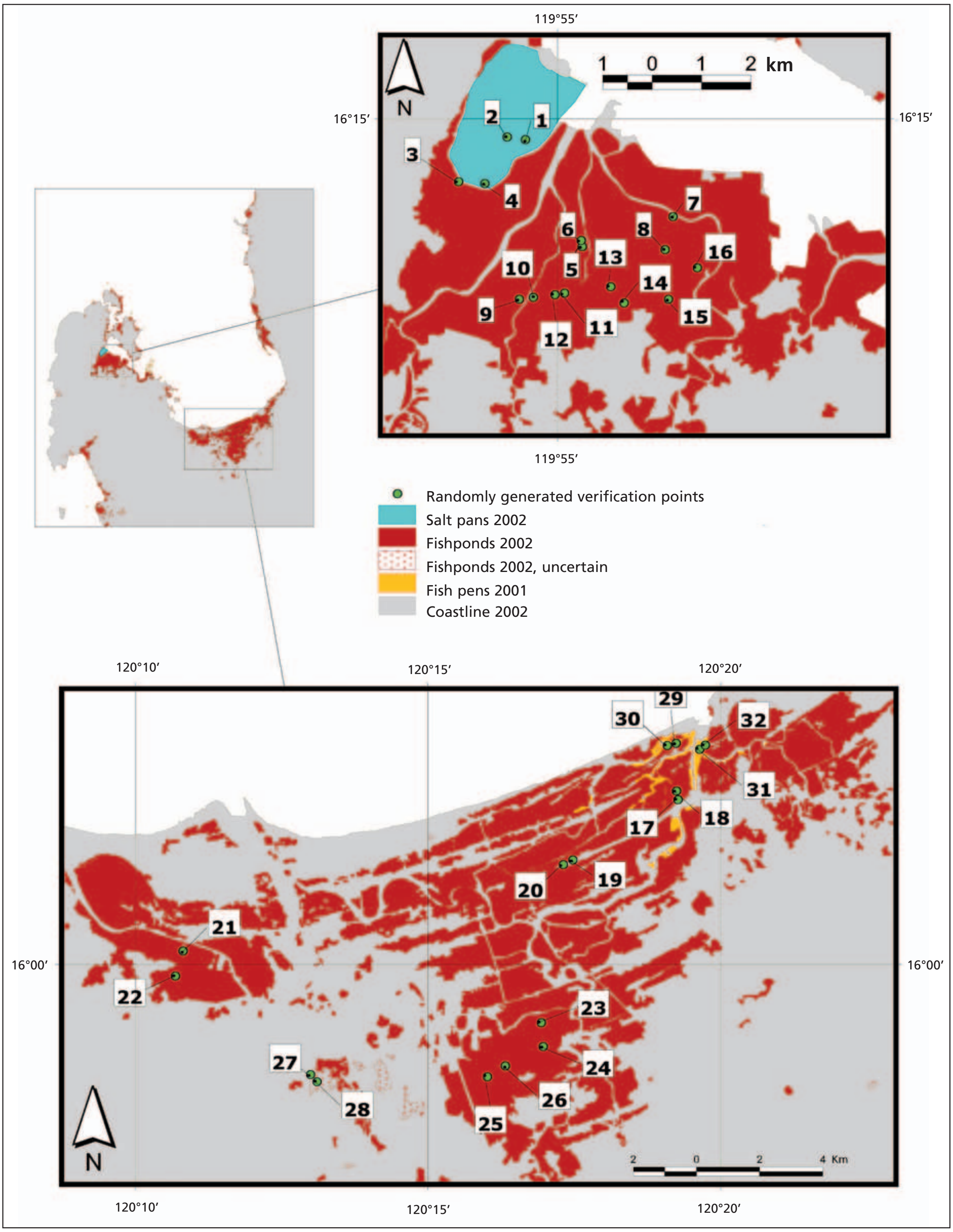


TABLE 8
Comparison of visual interpretation and *in situ* observations on the verification points

Point	Location	Visual interpretation	*In situ* verification
1	Zarragosa, Bolinao	Salt pans; fishponds across the river, south of the verification point	Salt pans; fishponds across the river, south of the verification point
2	Zarragosa, Bolinao	Salt pans	Salt pans
3	Lambes, Bani	Fishponds	Fishponds
4	Lambes, Bani	Salt pans	Salt pans
5	Bgy. Banog Norte, Bani	Fishponds	Fishponds
6	Bgy. Banog Norte, Bani	Fishponds	Fishponds
7	Pangapisan, Alaminos	Fishponds on both embankments of Embarcadero River	Fishponds on the north embankment of Embarcadero River; thin strip of residential area along the south embankment with fishponds behind it
8	Bani-Alaminos boundary, still a part of Bgy. Pangapisan	Fishponds	Marshland adjacent to salt pans in the north. Saltpans due south, converted to fishponds during the rain season
9	Bgy. Banog Norte, Bani	Fishponds	Fishponds
10	Bgy. Banog Norte, Bani	Fishponds	Fishponds
11	Bgy. Banog Norte, Bani	Fishponds	Fishponds
12	Bgy. Banog Norte, Bani	Fishponds	Fishponds
13	Bgy. Banog Norte, Bani	Fishponds	Fishponds
14	Bgy. Banog Norte, Bani	Fishponds	Fishponds
15	Bgy. San Miguel, Bani	Fishponds	Fishponds
16	Bgy. San Miguel, Bani	Fishponds	Fishponds
17	Bgy. Calmay, Dagupan City	Fishponds	Fishponds
18	Bgy. Calmay, Dagupan City	Fishponds	Fishponds
19	Bgy. Canaualan, Biec East, Binmaley	Fishponds	Fishponds
20	Bgy. Canaualan, Biec East, Binmaley	Fishponds	Fishponds
21	Bgy. Dulig, Lingayen	Fishponds	Fishponds
22	Bgy. Dulig, Lingayen	Fishponds	Fishponds
23	Bgy. Basing, Binmaley	Fishponds	Fishponds
24	Bgy. Basing, Binmaley	Fishponds	Fishponds
25	Bgy. Basing, Binmaley	Fishponds	Fishponds
26	Bgy. Basing, Binmaley	Fishponds	Fishponds
27	Bgy. Socony, Lingayen	Fishponds, uncertain	Swamp area
28	Bgy. Socony, Lingayen	Fishponds, uncertain	Water impoundment
29	Bgy. Pugaro, Dagupan City	Fish pens	Fish pens
30	Bgy. Pugaro, Dagupan City	Fish pens	Fish pens
31	Bgy. Pantal, Dagupan City	Fish pens	Fish pens
32	Bgy. Pantal, Dagupan City	Fish pens	Fish pens

The accuracy cannot be calculated for fish cages and traps, as they may have been moved or removed in the time interval between the image acquisition and the field verification, as a consequence of severe weather conditions. In fact, differences in their positions are visible on the 2001 and 2002 images, as explained above. Thus, mapping accuracy for fish cages was estimated at 90 percent and for fish traps at 70 percent. The results of the ground survey show that offshore fish traps are still approximately located in the same areas in which they were when the images were acquired, while the traps detected inside rivers were not observed in the two surveyed points.

The fish cages at the southern border of Santiago Island, clearly visible in all SAR images, are still located there, while the fish cages identified offshore Barangay Dori (Bolinao) are now replaced by fish pens built seaward from the rocky coastline (see appendix).

4. Discussion

4.1 RADARSAT FINE BEAM

RADARSAT fine beam data, thanks to their ground resolution of 6.25 m, provide excellent images of all aquaculture and fisheries structures considered in this study and, therefore, allow for their inventory and monitoring with great accuracy. As indicated in Table 4, fish pens were detected and easily mapped only with RADARSAT data. Similarly, fish traps were visible only on the RADARSAT image, but their mapping was not immediate due to the inherent characteristics of the traps themselves.

Having considered these evident advantages, some other aspects of RADARSAT data should be evaluated: a RADARSAT fine beam frame covers only 50 x 50 km at a cost of US$ 3 000 if the image has been already acquired and is available (archive data). Satellite programming cost is US$ 100 but goes up to US$ 500 if an acquisition date is booked in advance. For further information see http://www.rsi.ca/.

4.2 ERS SAR

ERS SAR data in their GEC format have a ground resolution of 12.5 m and cover a 100 x 100 km area. Fishponds and fish cages were easily mapped through ERS SAR data during this study with accuracy comparable to that of RADARSAT. An ERS SAR frame costs US$ 1 400 for both archived and programmed data.

In the present study we had the possibility of having ERS SAR data both in ascending and descending orbit. As discussed, this is a distinct advantage as it greatly increases detection and, thus, accuracy in fishponds mapping. For mapping fishponds and fish cages we recommend using ERS SAR with data from ascending and descending orbits acquired with a limited time interval between dates of recording. For further information see http://earth.esa.int/helpandmail/help_order.html or http://www.eurimage.com.

4.3 FINAL CONSIDERATIONS AND RECOMMENDATIONS

Mapping and monitoring coastal aquaculture and fisheries structures is extremely important for governments as this generates baseline information (e.g. see Tables 5 and 6 and appendix) for decision-making for a proper development of aquaculture and fisheries, including regulatory laws, environmental protection and revenue collection. This can be achieved with good accuracy and at regular intervals by satellite remote sensing, which allows observation of vast areas, often of difficult accessibility, at a fraction of the cost of traditional surveys. In several cases the information obtained through satellite remote sensing is unique, as it cannot be generated by any other means.

This study, and the other conducted previously in Sri Lanka (Travaglia, Kapestky and Profeti, 1999) have demonstrated that satellite imaging radar (SAR) data are unique for mapping aquaculture structures for two reasons: (1) for their inherent all-weather capabilities that are very important because aquaculture activities occur mainly in tropical and subtropical areas that aften are cloud covered, and (2) essentially because the backscatter from the fisheries structure components allows for their easy identification and separation from other natural and man-made features.

Other satellite sensors, operating in the visible and near-mid infrared portion of the electromagnetic spectrum are of questionable use for this task, as frequent cloud cover over the areas of interest impedes their use and also because of the very high possibility of misinterpretation of fishponds and other water-covered features, such as flooded rice paddies, marshes, etc.

The mapping accuracy obtained with SAR data is very high: 100 percent for fish pens and 95 percent for fishponds. It has been difficult to field check the mapping accuracy for fish cages, as they are floating and thus movable if need arises. However, their clear appearance on the SAR data, including information on their metallic/non metallic structure and the fact that they cannot be mistaken for any other object, permit a 90 percent estimated mapping accuracy.

Fish traps are detectable only on RADARSAT fine beam data, both offshore and inside river estuaries. Often their length can be measured. Being thin elongated structures almost completely under the water, their backscatter on SAR data should be maximum at low tide. Unfortunately, as indicated in section 2.1, tide information for the Lingayen Gulf was not available for the selection of the relevant data. Thus for fish traps it can be said that detectability on RADARSAT fine beam data is high and mapping accuracy can be estimated at 70 percent.

An extremely important aspect of aquaculture and fisheries structures mapping by satellite imaging radar (SAR) is that the resulting maps are geocoded and available in a Geographic Information System (GIS) as information layers. By adding other GIS layers such as land cover, urban development, tourist sites, areas subjected to conservation measures, potential/existing pollutants, water quality and other information layers of interest, the resulting database becomes a powerful tool for a proper management and development of the local resources, including environmental protection.

Another important aspect which should be considered is that the database facilitates identifying land cover changes which occurred during the development of the structures, mainly fishponds, and/or selection of the best places for their expansion, taking into account other potential and often conflicting uses of the area.

Although the hardware and software for remote sensing/GIS applications are available in almost all scientific institutions, the experience in handling SAR data is not common. Thus this report aims at the necessary technology transfer for an operational use of the approach indicated in other similar environments.

The present study complements two previous environmental and resources assessment for fisheries and aquaculture activities conducted in the Lingayen Gulf, namely the "Coastal Resources Management Profile" (McManus and Chua, 1990) and the "Socioeconomic Assessment" realized by BFAR in 2001. It could be used for fisheries and aquaculture development and management as well as for coastal area management of the Gulf.

Considering the low cost and precision of the methodology utilized for the aquaculture and fisheries structures mapping in the Lingayen Gulf, it should be expanded to cover all other areas of interest. The resulting database could constitute a powerful tool, essential for any decision-making concerning the management and development of these activities and could promote responsible fisheries by improving the sustainability of aquaculture and fisheries.

This would be easily accomplished by the creation of a GIS Unit in BFAR, including the necessary technology transfer, and by fostering, maybe with a FAO catalytic role at the beginning, close cooperation between BFAR and the existing local institutions having expertise in remote sensing and GIS, such as the National Mapping and Resource Information Authority (NAMRIA) and the Bureau of Soils and Water Management (BSWM).

5. Glossary

C-band. Portion of the microwave region of the electromagnetic spectrum, including waves with frequencies comprised between 4 and 8 GHz (corresponding to wavelengths ranging between 7.5 to 3. 75 cm).

Cell. Element of a data grid or data matrix. Each cell corresponds to a portion of the ground surface. The value associated to each cell represents either a thematic attribute or the average value of a parameter, associated to the corresponding surface.

Ellipsoid. The Earth surface is approximately described by an ellipsoid, a closed surface all planar sections of which are ellipses. In general, an ellipsoid has three independent axes, and is usually specified by the length of the three semi-axes. If the lengths of two axes are the same, the ellipsoid is called "ellipsoid of revolution" or spheroid. Due to the rotation around its axis, the Earth has the shape of a spheroid. Several spheroids are used to model the Earth surface and project it onto a two-dimensional map; the choice of the reference spheroid depends on the region of the Earth to be represented and the required precision. The spheroids quoted in this work are Clarke 1866, WGS72 and WGS84. Clarke 1866 is used to map the North America and the Philippines. The World Geodetic System (WGS) spheroids have been developed to be used for global mapping; the number indicates the year of calculation. WGS84 is the most recent version, and is also used by the Global Positioning System.

Geocoding. Procedures applied to a satellite image to generate a new image with the projection and scale properties of a map. In particular, map coordinates are associated to the center point of each element (pixel) of the resulting image.

GIS (Geographic Information System). A collection of computer hardware, software, and geographic data for capturing, storing, updating, manipulating, analysing, and displaying all forms of geographically referenced information.

GPS (Global Positioning System). A constellation of twenty-four satellites, developed by the U.S. Department of Defence, that orbits the Earth at an altitude of 20 200 km. These satellites transmit signals that allow a GPS receiver anywhere on Earth to calculate its own location. The Global Positioning System is used in navigation, mapping, surveying, and other applications where precise positioning is necessary.

Landsat. The U.S. Landsat satellites are the first series of Earth Observation satellites providing global, repeated coverage of the Earth surface. The sensors onboard these satellites operate in the visible up to middle infrared wavelengths, and in the thermal infrared. The first satellite of the mission, ERTS-1 (later renamed Landsat-1) was launched in 1972. The current Landsat-7 mission hosts the Enhanced Thematic Mapper sensor; of its nine channels, seven acquire data in the visible up to middle infrared, at 30 m resolution. More information on the Landsat-7 mission can be found in the USGS Web pages (http://landsat7.usgs.gov/index.php) and in the NASA Web pages (http://landsat.gsfc.nasa.gov/).

Pixels (Picture elements). Cells of an image matrix. The ground surface corresponding to the pixel is determined by the instantaneous field of view (IFOV) of the sensor system, e.g. the solid angle extending from a detector to the area on the ground it measures at any instant. The digital values of the pixels are the measures of the radiant flux of electromagnetic energy emitted or reflected by the imaged Earth surface in each sensor channel.

Polygon. In a GIS framework, a polygon is a closed line (or a closed set of lines) representing a surface. The surface is generally homogeneous with respect to some criteria; for example, land use or type, administrative units, etc. Map coordinates (easting, northing and height) are associated to the vertices of the polygon.

Polyline. In a GIS framework, a polyline is a set of straight line segments (connected or not) representing a linear geographic feature, such as a road or a railway. The polyline may also connect points homogeneous with respect to some criteria, such as a contour line. Map coordinates (easting, northing and height) are associated to the vertices of the segments.

RADARSAT. Canada's series of remote sensing satellites. RADARSAT-1 was launched on November, 1995; RADARSAT-2 will be presumably launched on 2005. RADARSAT-1 hosts a Synthetic Aperture Radar (SAR), an active sensor operating in the microwave portion of the electromagnetic spectrum at C-band in HH polarization. The SAR operates in seven different acquisition modes, with spatial resolution ranging from 6.25 to 100 m. RADARSAT-2 will carry an enhanced version of the same sensor. More details on RADARSAT-1 and -2 are available in the Canadian Space Agency Web pages (http://www.space.gc.ca/asc/eng/csa_sectors/earth/radarsat1/radarsat1.asp and …/radarsat2/radarsat2.asp).

SAR (Synthetic Aperture Radar). An imaging radar is an active instrument that transmits microwave pulses toward the Earth surface and measures the magnitude of the signal scattered back towards it. The return signals from different portions of the ground surface are combined to form an image. A Synthetic Aperture Radar (SAR) is a special type of imaging radar. It is a complex system that measures both the amplitude and phase of the return signals; their analysis exploits the Doppler effect created by the motion of the spacecraft with respect to the imaged surface to achieve high ground resolution. As the source of the electromagnetic radiation used to sense the Earth surface is the system itself, it can be operated during day and night. The atmospheric transmittance in the microwave interval used by remote sensing SAR systems (2 to 30 GHz) is higher than 90%, also in presence of ice and rain droplets (except under heavy tropical thunderstorms); thus, SAR can acquire data in all weather conditions.

Scale. The ratio between a distance or area on a map and the corresponding distance or area on the ground.

Shapefile. A vector file format for storing the location, shape, and attributes of geographic features.

Spatial Resolution. The area of the ground surface corresponding to a pixel in a satellite image.

Speckle. Noise affecting Synthetic Aperture Radar (SAR) images. The noise is created by constructive and destructive interference between the backscattered energy from different portions of the ground surface included in the same pixel of the SAR image. The value of the pixel is thus increased or decreased; the SAR image appears to be covered by randomly scattered bright and dark spots.

SPOT (Système Pour l'Observation de la Terre). French Earth Observation satellites operating in the optical wavelengths. The first satellite, SPOT-1 was launched in 1986; the most recent satellite, SPOT-5, was launched in 2000. Among its instruments, the HRG acquires data in five channels useful to study land cover: a panchromatic channel (spatial resolution 2.5 or 5 m), three channels in the visible and near infrared wavelengths (spatial resolution 10 m) and one channel in the short-wave infrared (spatial resolution 20 m). More information on the SPOT satellites can be found at the SPOT Image Web site (http://www.spotimage.com) and at the CNES Web site (http://www.cnes.fr).

UTM (Universal Transverse Mercator). A commonly used projected coordinate system that divides the globe into 60 zones, starting at -180° longitude. Each zone extends north-south from 84° North to 80° South, spans 6° of longitude, and has its own central meridian.

Vector. A data structure used to represent geographic features. Features are represented by points, lines or polygons. A line is made up of connected points (vertices), and a polygon of connected lines. Map coordinates (easting, northing and height) are associated to each point or vertex in a vectorial feature. Attributes are also associated with each feature (as opposed to the raster data structure, which associates attributes with grid cells).

Sources:
Drury, S.A. 1998. *Images of the Earth - A Guide to Remote Sensing Second Edition*. Oxford, UK. Oxford University Press, 212 pp.

ESRI. 2001. *The ESRI Press dictionary of GIS terminology*. Environmental Systems Research Institute, Inc. Redlands, California, USA (available at http://www.esri.com/library/glossary/a_d.html).

Swain P.H. & Davis, S.M. 1978. *Remote Sensing: The Quantitative Approach.* New York, USA. McGraw-Hill, 396 pp.

References

Benetti, D.D., Clark, A. & Feeley, M.W. 1999. Feasibility of selected candidate species of marine fish for cage aquaculture development in the Gulf of Mexico with novel remote sensing techniques for improved offshore systems monitoring. *In* Proceedings 3rd Open Ocean Aquaculture Conference, Corpus Christi, Texas, USA, 10–15 May 1998, pp. 103–119. Bryan, Texas, USA, Texas Sea Grant College Program.

Beveridge, M.C.M. 1987. *Cage aquaculture*. Farnham, Surrey, UK, Fishing News Books Ltd. 351 pp.

BFAR. 2001. Lingayen Gulf Resource and Socio-economic Assessment (RSA), Terminal Report. Fisheries Resource Management Project (ADB Loan Nos. 1562/1563-PHI and JBIC Loan No. PH-P197) Draft Copy (Unpublished). 406 pp.

Fingas, M. & Brown, C.E. 2000. Review of Oil Spill Remote Sensing. *In* Proceedings SPILLCON 2000: 8th International Oil Spill Conference, Darwin, Australia, 15–17 August 2000, 23 pp. (available at http://www.aip.com.au/amosc/spillcon/speakers.htm).

Frost, V.S., Stiles, J.A., Shanmugan, K.S. & Holtzman, J.C. 1982. A model for radar images and its application to adaptive digital filtering of multiplicative noise. IEEE Transaction on Pattern Analysis and Machine Intelligence, Vol. 4, pp. 157–166.

Hesselmans, G.H.F.M., Wensink, G.J., Prasetya, G. & Barnas, I. 2000. Mapping of Indonesian coastal waters by synthetic aperture radar: an Indonesian-Netherlands initiative for starting a new business. *In* Proceedings ESA ERS-ENVISAT Symposium "Looking down to Earth in the New Millennium", Gothenburg, Sweden, 16–20 October 2000, 10 pp. (available at http://earth.esa.int/pub/ESA_DOC/gothenburg/1105hess.pdf).

Hogda, K.A. & Malnes, E. 2002. Use of RADARSAT F5 images for detection and positioning of fish cages. *In* Proceedings IEEE Geoscience and Remote Sensing Symposium 2002, Vol. 5, pp. 3047–3049.

Lee, J.S. 1980. Digital image enhancement and noise filtering by use of local statistics. IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-2, pp. 165–168.

Lee, J.S. 1981. Refined filtering of image noise using local statistics. Computer Graphics and Image Processing, Vol. 4, pp. 380–389.

Li, C. 1988. Two adaptive filters for speckle reduction in SAR images by using the variance ratio. International Journal of Remote Sensing, Vol. 9, pp. 641–653.

Lopez, N.A. 1991. Progress of Seafarming activities, research and development in the Philippines. Country report presented at the Fifth National Coordinators Meeting of the FAO/UNDP Regional Seafarming Development and Demonstration Project. 5–8 November 1991, Bangkok, Thailand.

McManus, L.T. & T.E. Chua. 1990. The coastal environment profile of Lingayen Gulf, Philippines. ICLARM Technical Report No. 22, 69 pp. International Center for Living Aquatic Resources Management, Manila, Philippines.

Mouchot, M.C., Sweeney, R. & De Lisle, D. 1990. Use of Radar Imagery as an Aid in the Management of Aquaculture Sites. *In* Proceedings 13th Canadian Symposium on Remote Sensing, Fredericton, New Brunswick, Canada, 16–19 July 1990, pp. 326–337. Ottawa, Canada, Canada Centre For Remote Sensing.

Muir, J.F. 1995. Aquaculture development trends: perspectives for food security. Japan/FAO Intern. Conf. on Sustainable Contribution of Fisheries to Food Security, Kyoto, Japan, 4–9 December 1995. Doc. KC/FI/95/TECH/4. 133 pp.

NAMRIA. 1977. Topographic maps of the Philippines, scale 1:50 000, sheets Santa Cruz, Bolinao, Alaminos, San Carlos, Dagupan City, Bugallon, Aringay, Lingayen, Bangar, San Fernando. National Mapping and Resources Information Authority, Metro Manila.

Palma, A. 1989. Patterns and levels of aquaculture practices in the coastal municipalities adjoining Lingayen Gulf. *In* Proceedings ASEAN/US Coastal Resources Management Project Workshop "Towards sustainable development of the costal resources of Lingayen Gulf, Philippines", Bauang, La Union, Philippines, 25–27 May 1988. Metro Manila, Philippines, Philippine Council for Aquatic and Marine Research and Development. ICLARM Conference Proceedings No. 17, pp. 71–82.

Palma, A., Legasto, R. & Paw, J. 1989. Mariculture as an alternative source of livelihood for sustenance fishermen in Lingayen Gulf. *In* Proceedings ASEAN/US Coastal Resources Management Project Workshop "Towards sustainable development of the costal resources of Lingayen Gulf, Philippines", Bauang, La Union, Philippines, 25–27 May 1988. Metro Manila, Philippines, Philippine Council for Aquatic and Marine Research and Development. ICLARM Conference Proceedings No. 17, pp. 125–132.

Paringit, E.C., Lopez, E.D., Galeon, F.A. & Vinluan, R.J.N. 1998. Polarimetric Radar Data Analysis of Key Landcover Features in the Coastal Panay Area: A Preparatory Tool for Polarimetric SAR Image classification. *In* Proceedings 19th Asian Conference on Remote Sensing, Manila, Philippines, 16–20 November 1998, 2 pp. (available at http://www.gisdevelopment.net/aars/acrs/1998/ts8/ts8002.shtml).

Paw, J.N., Diamante, D.A.D., Robles, N.A., Chua, T.-E., Quitos, Jr. L.N. & Cargamento, A.G.A. 1992. Site selection for brackishwater aquaculture development and mangrove reforestation in Lingayen Gulf, Philippines using geographic information systems. *In* Proceedings Canadian Conference on GIS, Ottawa, Ontario, Canada, 24–26 March 1992, Canadian Institute of Surveying, pp. 821–823.

Petit, M., Stretta, J.M., Farrugio, H. & Wadsworth, A. 1992. Synthetic aperture radar imaging of sea surface life and fishing activities. *IEEE Trans. Geosci. Remote Sens.*, 30: 1085–1089.

Polngam, S. 2001. Operational use of RADARSAT and optical data for coastal land cover mapping. *In* Proceedings 22nd Asian Conference on Remote Sensing, Singapore, China, 5–9 November 2001, Vol. 2, pp. 1037–1041. (available at http://www.crisp.nus.edu.sg/~acrs2001/pdf/156POLNG.pdf).

Profeti, G., Travaglia, C. & Carlà, R. 2003. Detecting and monitoring aquacultural patterns through multitemporal SAR imagery analysis. *In* Proceedings V EUROPTO Conference "Remote Sensing for Agriculture, Ecosystems and Hydrology IV" Agia Pelagia, Crete, Greece, 23–27 September 2002. SPIE, Vol. 4879, pp. 410–418.

Shehadeh, Z. 2002. Aquaculture country profile. Draft internal FAO/FI document. Rome, FAO.

Touzi, R. 1999. On the use of polarimetric SAR data for ship detection. *In* Proceedings IEEE Geoscience and Remote Sensing Symposium 1999, Hamburg, Germany, 28 June – 7 July, 1999. Vol. 2, pp. 812–814.

Travaglia, C., Kapetsky, J.M. & Profeti, G. 1999. Inventory and monitoring of shrimp farms in Sri Lanka by ERS SAR data. FAO Environment and Natural Resources Working Paper No. 1, 34 pp. (available at http://www.fao.org/sd/EIdirect/EIre0077.htm).

Tuell, G.H., Lucas, J.R. & Graham, D.B. 1999. An Accuracy Assessment of Shoreline Data for Castle Bay, Alaska, Compiled from Synthetic Aperture Radar. *In* Proceedings Oceans '99 MTS/IEEE "Riding the Crest into the 21st Century", Seattle, USA, 13–16 September 1999. IEEE, Vol. 3, pp. 1325–1332.

Welcomme, R.L. (comp.). 2001. *Inland fisheries. Ecology and management*. Oxford, UK, FAO/Fishing News Books. 358 pp.

Recommended further reading

(Relevant papers and Web pages not cited in the main document)

USE OF RADAR IMAGERY FOR AQUACULTURE PLANNING AND MANAGEMENT

Web pages

Niemann, K.O. 2002. The Use of RADARSAT Imagery to Detect, Identify, and Map Land Use Practices in South East Asia. Department of Geography, University of Victoria (available at http://www.space.gc.ca/asc/eng/csa_sectors/technology/development/industry/programs/dru/dru0301.asp).

RADARSAT International. RADARSAT-1 Beams - Which to Choose. *In* RADARSAT Illuminated, Your Guide to Products and Services (available at http://www.asf.alaska.edu/R1beamChoice.pdf).

Staples, G.C., Hurely, J. & Burns, R.S. 1998. Coastal Zone Monitoring with RADARSAT-1. RADARSAT International (available at http://www.gisdevelopment.net/aars/acrs/1998/ts7/ts7004.shtml).

USE OF RADAR IMAGERY FOR IDENTIFYING AQUACULTURE STRUCTURES

Relevant papers

Clemente-Colón, P., Xiaofeng L., Zheng, Q., Yan, X.H., Bertoia, C., Chang, P., Pichel, W.G. & Friedman, K.S. 2000. SAR Observations of the Bohai Sea and the Korea bay region. Camp Springs, MD, USA, U.S. Department of Commerce NOAA/NESDIS/ORA (available at http://www.natice.noaa.gov/pub-info/Clemente_PORSEC2000.htm).

Ross, S., Brisco, B., Brown, R.J., Yun, S. & Staples, G.C. 1998. Paddy Rice Monitoring with RADARSAT-1. *In* Proceedings of 19th Asian Conference on Remote Sensing, 16–20 November 1998, Manila, Philippines (available at http://www.gisdevelopment.net/aars/acrs/1998/ts1/ts1004.shtml).

Staples, G.C. & Hurley, J. 1996. Rice Crop Monitoring in Zhaoqing, China using RADARSAT SAR - Initial Results. *In* Proceedings of 17th Asian Conference on Remote Sensing, 4–8 November 1996, Sri Lanka (available at http://www.gisdevelopment.net/aars/acrs/1996/ts1/ts1001.shtml).

Staples, G.C., Rossignol, S., Nazarenko, D., Elms, G., Wang, C., Guo, H., Brown, R. & Brisco, B. 1994. Rice Crop Monitoring using RADARSAT simulated SAR Imagery. *In* Proceedings 15th Asian Conference on Remote Sensing, pp. 1–5, Vol I, Bangalore, India, 17–23 November 1994 (available at http://www.gisdevelopment.net/aars/acrs/1994/ts1/ts1001.shtml).

Web pages

Kalensky, Z., Fadaie, K. & Whitney, L. 1996. Overview of Canada Centre for Remote Sensing (CCRS) activities in Asia (available at http://www.gisdevelopment.net/aars/acrs/1996/ts6/ts6002pf.htm).

RADARSAT INTERNATIONAL. Surveillance - Aquaculture Detection with RADARSAT-1 (available at http://www.geomap.com.au/radarsat_surv8.htm).

RADARSAT INTERNATIONAL. Marine Surveillance - Aquaculture Site Detection (available at http://www.rsi.ca/rsic/marine/ms_aqua.asp).

Staples, G.C. 2001. RADARSAT-1 Operational Applications. Aquaculture mapping. Inventory and productivity estimation. RADARSAT International (available at http://orbit-net.nesdis.noaa.gov/orad/sarconference/staples_applications.pdf).

USE OF RADAR IMAGERY FOR PLANNING AND MANAGEMENT OF FISHERIES

Relevant papers

Boivin, T.G.,. Coates, D & Werle, D. (in press). Remote sensing applications for information generation and monitoring for large river basin fisheries in tropical developing countries. *In* Proceedings of Second International Symposium on the Management of Large Rivers for fisheries, February 2003, Phnom Penh, Cambodia (available at http://www.lars2.org/unedited_papers/unedited_paper/Boivin.pdf).

Boivin, T.G. & Werle, D. (in press). Using RADARSAT -1 SAR Data for Fisheries and Wetland Habitat Assessment in the Lower Mekong River Basin, South-East Asia. *Canadian Journal of Remote Sensing.*

Suga, Y., Oguro, Y. & Takeuchi, S. 1999. Detection of Oyster Beds Using Sar and Optical Sensor Data. *In* Proceedings of 20th Asian Conference on Remote Sensing, 22–25 November 1999, Hong Kong, China (available at http://www.gisdevelopment.net/aars/acrs/1999/ps2/ps2128.shtml).

Web pages

Boivin T.G. 2003. Monitoring the Mekong River. Hatfield Consultants, Ltd. Vancouver, Canada (available at http://www.space.gc.ca/asc/pdf/id_hatfield.pdf).

Hatfield Consultants, Ltd. 2000. Using RADARSAT for Improving Fisheries Management and Food Security in the Mekong River Watershed, Southeast Asia (available at http://www.hatfieldgroup.com/featured/mek.htm).

Hatfield Consultants, Ltd. (in press). Projects Involving RADARSAT Technology. Mekong Fisheries Habitat Assessment Using RADARSAT (available at http://www.hatfieldgroup.com/featured/radarsat.htm).

COASTAL ZONE MANAGEMENT AND NATURAL RESOURCE MANAGEMENT (LINGAYEN GULF, PHILIPPINES)

Relevant papers

Cruz-Trinidad, A., Alojado, Z. & Cargamento, A.G.C. 1996. Options for land use management in Lingayen Gulf, Philippines. *In* A., Cruz-Trinidad, A., ed. *Valuation of tropical coastal resources: theory and application of linear programming*, pp. 64–77. ICLARM Stud. Rev. 25, Manila, Philippines, ECLAC-ICLARM. 108 pp.

Gomez, E.D. & Talaue-McManus, L. 1996. Case study 4: Coastal management in Bolinao Town and the Lingayen Gulf, Philippines. *In* GESAMP, *The contribution of science to integrated coastal management*, pp. 57–66. Report Study No. 61, 66 pp.

NEDA, Region I (National Economic Development Authority, Region I, Philippines). 1992. The Lingayen Gulf coastal area management plan. ICLARM Tech. Rep. No. 32. Manila, Philippines, Philippine Council for Aquatic and Marine Research and Development, 87 pp.

Web pages

NAMRIA. 1997. National Priority Project: Philippines. Coastal Zone Environmental and Resource Management Project (CZERMP) - Phase III of the ASEAN Australia Economic Cooperation Program (AAECP) (available at http://www.amsat.com.au/czermp/level_1/countries/czphdfww.html).

AQUACULTURE (LINGAYEN GULF, PHILIPPINES)

Relevant papers

FAO. 1999. *Rural aquaculture in the Philippines*. RAP-FAO Publication No.1999/20, Bangkok, Thailand. 102 pp.

Lopez, N.A. 1995. Annex II-14 Philippines. *In* FAO/NACA, Regional Study and Workshop on the Environmental Assessment and Management Development. NACA Environment and Aquaculture Development Series No. 1. Bangkok, Thailand, Network of Aquaculture Centres in Asia-Pacific. 503 pp. (available at http://www.fao.org/docrep/field/003/AC279E/AC279E00.htm).

Palma, A., Legasto. R. & Paw, J. 1989. Mariculture as an alternative source of livelihood for sustenance fishermen in Lingayen Gulf, p. 125–132. *In* E., Silvestre, E., Miclat & T.-E Chaua, eds. *Towards the sustainable development pf coastal resources of Lingayen Gulf, Philippines*. ICLARM Conference Proceedings 17. Philippine Council for Aquatic and Marine Research and Development, Los Baños, Laguna, and International Center for Living Aquatic Resources Management, Makati, Metro Manila, Philippines. 200 pp.

Silvestre, G.T. & Palma, A.L. 1990. Economic sector - Coastal Aquaculture. *In* L.T. McManus & T.-E. Chua, eds. *The Coastal Environmental Profile of Lingayen Gulf, Philippines,* pp.29–31. ICLARM Technical Reports No. 22, Manila, Philippines, International Center for Living Aquatic Resources Management. 69 pp.

Sumalde, Z.M., Francisco, K.L.A. & Peñales, M.H. 2002. Aquaculture pollution in Bolinao: who pays the price? *In* Proceedings of the Coastal Zone Asia Pacific Conference, 11–17 May 2002, Bangkok, Thailand (available at http://www.vims.edu/czap/poster/Sumalde_Zenaida.ppt).

Sumalde, Z.M., Francisco, K.L.A. & **Peñales, M.H.** 2002. Pollution-induced fish kills in Bolinao: effects of excessive aquaculture structures and overstocking. Economy and Environment Program for Southeast Asia EEPSEA Technical Paper, Tanglin, Singapore (available at http://www.eepsea.org/en/ev-32065-201-1-DO_TOPIC.html).

FISHERIES (LINGAYEN GULF, PHILIPPINES)

Relevant papers

Calud, A., Rodriguez, G., Aruelo, R., Aguilar, G., Cinco, E., Armada, N. & Silvestre, G. 1989. Preliminary results of a study of the municipal fisheries in Lingayen Gulf. *In* G., Silvestre, E., Miclat, & Thia-Eng Chua, eds. *Towards sustainable development of the costal resources of Lingayen Gulf, Philippines*, pp. 3–29. ICLARM Conference Proceedings No. 17. Manila, Philippines, Philippine Council for Aquatic and Marine Research and Development and International Center for Living Aquatic Resources Management. 200 pp.

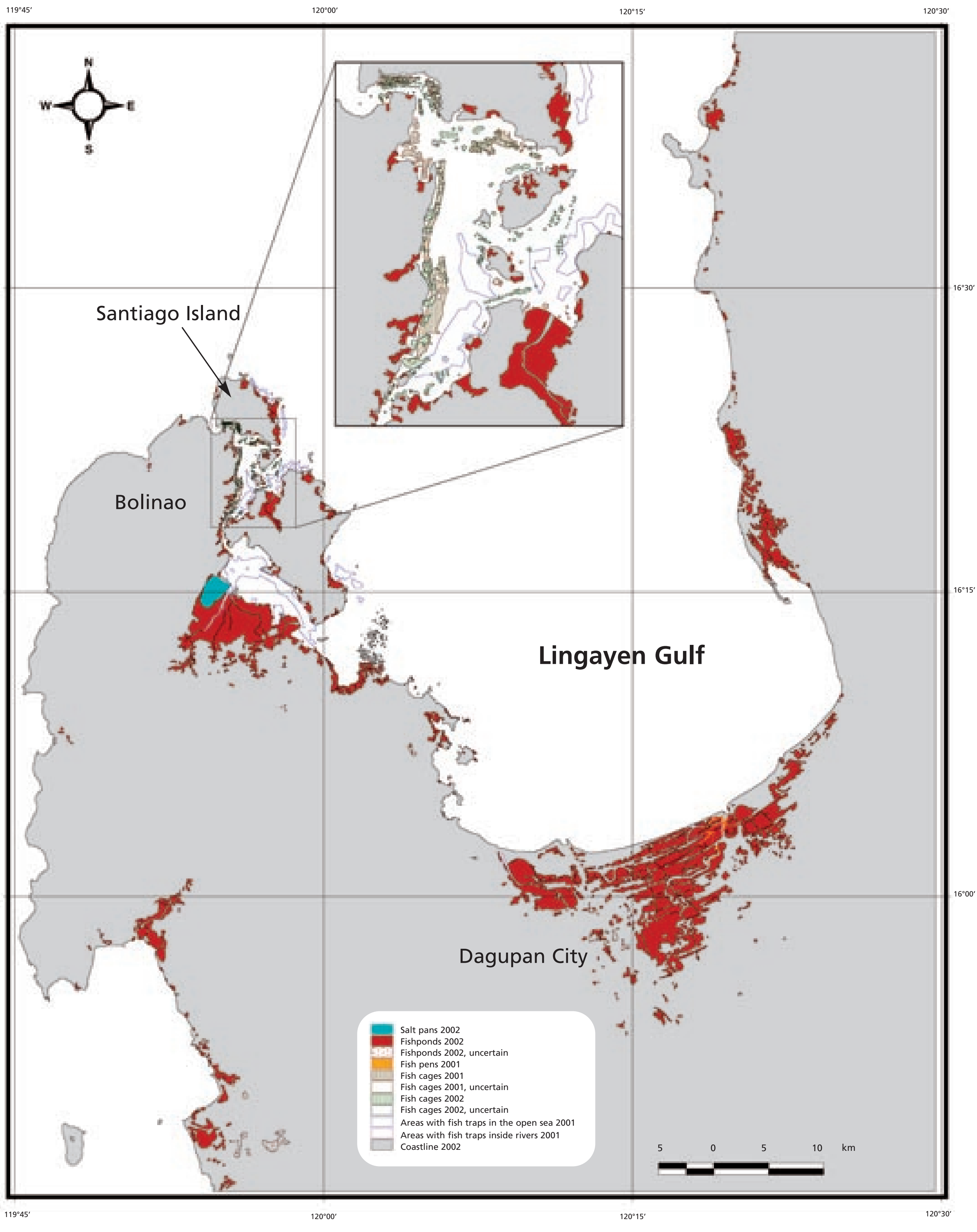
Guerrero, R.D. III. & Soesanto, V. 1981. Report. Training course on small-scale pen and cage culture for finfish. Laguna (Philippines) Aberdeen (Hong Kong). 26 October 1981. South China Sea Fisheries Development and Coordinating Programme, Manila, Philippines. UNDP Project. 77 pp.

Umali, A.F. 1950. Guide to the Classification of Fishing Gear in the Philippines. Research Report No. 17. Fish and Wildlife Service of the US Dept. of the Interior. 165 pp.

Appendix

Map of coastal aquaculture and fisheries structures in Lingayen Gulf, the Philippines

Mapped by visual interpretation of the RADARSAT-1 image of 4 February, 2001 and the ERS-2 SAR images of 2 and 23 December, 2002


119°45′
120°00′
120°15′
120°30′
16°30′
16°15′
16°00′
N
S
W
E
Santiago Island
Bolinao
Lingayen Gulf
Dagupan City
Salt pans 2002
Fishponds 2002
Fishponds 2002, uncertain
Fish pens 2001
Fish cages 2001
Fish cages 2001, uncertain
Fish cages 2002
Fish cages 2002, uncertain
Areas with fish traps in the open sea 2001
Areas with fish traps inside rivers 2001
Coastline 2002
5 0 5 10 km

Inventory and monitoring of coastal aquaculture and fisheries structures provide important baseline data for decision-making in planning and development, including regulatory laws, environmental protection and revenue collection. Mapping these structures can be performed with good accuracy and at regular intervals by satellite remote sensing, which allows observation of vast areas, often of difficult accessibility, at a fraction of the cost of traditional surveys.
Satellite imaging radar (SAR) data are unique for this task not only for their inherent all-weather capabilities, very important as aquaculture activities mainly occur in tropical and subtropical areas, but essentially because the backscatter from the structure components allows for their identification and separation from other features.
The area selected and object of the study has been Lingayen Gulf, sited in Northwestern Luzon Island, the Philippines, where all these structures of interest occur.
Field verification of the methodology resulted in the following accuracy: fishponds 95 percent, fish pens 100 percent.
Mapping accuracy for fish cages was estimated at 90 percent and for fish traps at 70 percent.
The study is based on interpretation of SAR satellite data and a detailed image analysis procedure is described. The report aims at the necessary technology transfer for an operational use of the approach indicated in other similar environments.

ISBN 92-5-105114-3 ISSN 0429-9345

9 789251 051146

TC/M/Y5319E/1/03.04/2750